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UC-60

# ASI/PINSON 1kW HIGH RELIABILITY WIND SYSTEM

Phase II

Prototype Construction and Testing

July 1981

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## FOREWORD

This report was prepared by Aerospace Systems, Inc. (ASI), Burlington, Massachusetts as prime contractor, and Pinson Energy Corporation (PEC), Marstons Mills, Massachusetts and Natural Power Inc. (NPI), New Boston, New Hampshire, as subcontractors for Rockwell International, Atomics International Division, Golden, Colorado under Contract No. PF71777-F. Rockwell International operates a Department of Energy installation at Rocky Flats, Colorado. The study was sponsored by the Energy Systems Group at the Rocky Flats Plant. Mr. Warren S. Bollmeier, II served as Technical Monitor of the Contract. This report summarizes Phase II, Fabrication and Testing, of the design and development of a 1-kW high-reliability vertical-axis small wind energy conversion system (SWECS).

The effort was directed by Mr. John Zvara, President and Program Manager of ASI. Mr. Richard B. Noll served as Project Engineer. The turbine was fabricated and tested under subcontract to Pinson Energy Corporation under the direction of Mr. Herman M. Drees, President of PEC. The electrical system was fabricated and tested under subcontract to Natural Power Inc. Mr. Richard L. Katzenberg, President of NPI, served as the NPI Program Manager and Mr. Leander B. Nichols served as their Project Engineer.

# ABSTRACT

Aerospace Systems, Inc. (ASI) joined with Pinson Energy Corporation (Pinson) and Natural Power Inc. (NPI) in the development of a 1-kW high-reliability SWECS. The approved design is a 15-ft vertical-axis turbine with three straight 8-ft blades controlled by a tilt-cam mechanism. The tilt-cam mechanism controls blade cyclic pitch amplitudes in a manner similar to a helicopter swash plate. The turbine rotor has a calculated power coefficient of 0.4 at an optimum tip speed ratio of ~ 3.0 which results in a rotational speed of 112 RPM in a 9 m/sec wind.

The electrical system provides 1-kW of 24 V DC power in a 9 m/sec wind by means of a flux-switching alternator. The electronic circuitry, designed with high-reliability components, consists of a voltage regulator and a power rectifier. A dump-load circuit is provided as an option. Two transient protection networks are included, one on the tower for the alternator and the other to protect circuitry in the control building.

Three prototypes were fabricated and extensive testing was conducted on the first unit. Pinson fabricated the turbines and tested the complete prototype. NPI fabricated and tested the prototype electrical systems. Both ASI and NPI assisted in testing of the prototype system.

Prototype tests showed that the SWECS operated as designed although output at 20 MPH was slightly lower than 1-kW. A system power coefficient of 0.25 was obtained in intial tests. Design changes were made as a result of tests, the most noticeable change being the replacement of the approved vertical tail vane and horizontal wing with a V-vane configuration. Poor wind conditions precluded completion of acceptance testing. As a result, Rockwell performed controlled velocity tests (CVT) of the first prototype prior to field tests.

Additional effort approved under Phase II included instrumentation for the first prototype; design, fabrication and testing of equipment for manual installation; and preparation of an assembly, operation and maintenance manual.

Design of the 1-kW High-Reliability SWECS was completed under Phase I of the joint effort. Fabrication of three prototype units and testing by the manufacturer of the first prototype were done during Phase II. This report documents the completion of Phase II.

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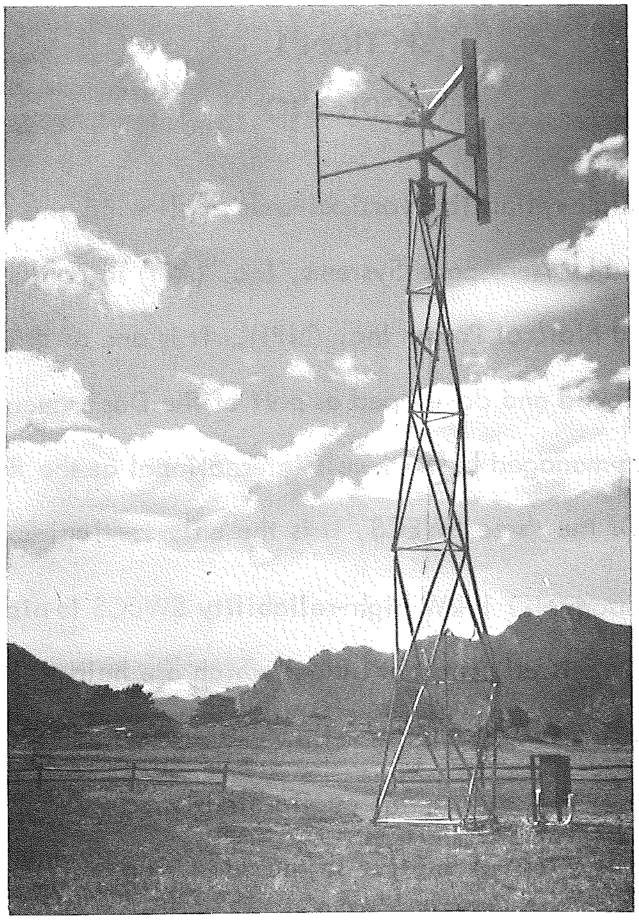
# SECTION 1

# INTRODUCTION

The 1-kW high-reliability vertical-axis small wind energy conversion system (SWECS) was developed by Aerospace Systems, Inc. (ASI) in conjunction with Pinson Energy Corporation and Natural Power Inc. (NPI). It is one of three different high-reliability SWECS designed and developed as part of the Department of Energy SWECS program which is being managed by Rockwell International at the Rocky Flats Plant near Golden, Colorado. Of the three SWECS, it is the only vertical-axis design.

The ASI/Pinson/NPI 1-kW high-reliability SWECS is pictured in Figure 1. The turbine has three untwisted, straight blades which are held to a central shaft by streamlined support struts. The blades follow a preset schedule of angle changes during each revolution of the rotor. This cyclic blade pitch motion is activated by a mechanical cam which is oriented relative to the wind by a wind-direction tracking vane (in a V-configuration) mounted above the machine. By introducing sufficient initial blade angle into the cyclic pitch schedule, the turbine becomes self-starting. In high winds, the blades are pivoted to a position of least wind resistance making the rotor aerodynamically self-limiting. This is achieved through a mechanism which, when acted on by the combination of high centrifugal loads associated with increased rotational rate and of aerodynamic downloads on the V-vane, changes the cyclic pitch schedule so that the blades are aerodynamically stalled.

The SWECS as shown in Figure 1 is basically the same as approved at the Phase I Final Design Review. The most noticeable change is the replacement of the approved tail/wing vane with the V-vane configuration. A 42.5-ft Octahedron tower was approved for installation at the Rocky Flats Wind Systems Test Center (WSTC). Additional effort was approved in Phase II for the installation of instrumentation on the



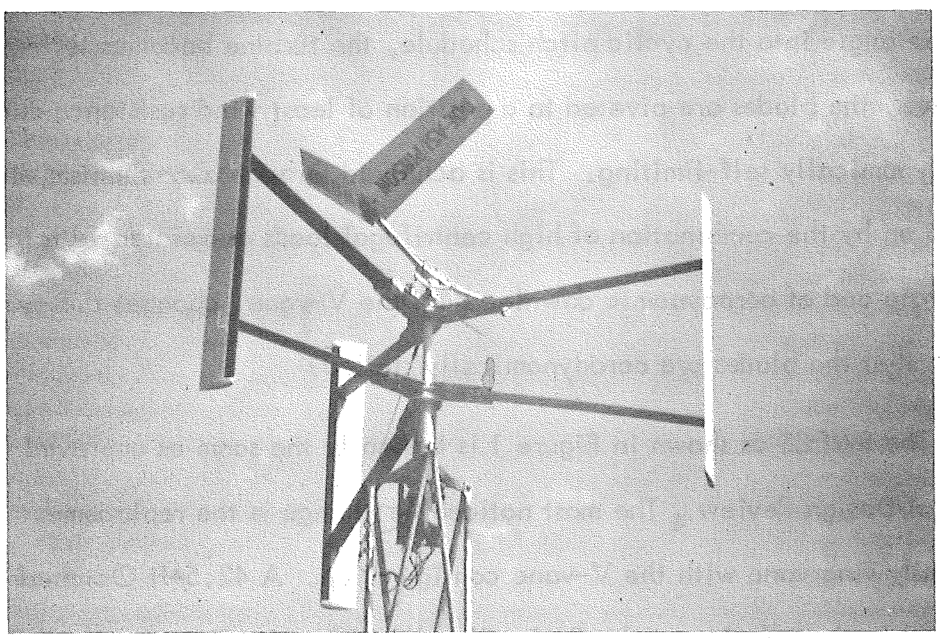


Figure 1. ASI/Pinson/NPI 1-kW High-Reliability SWECS.

first prototype, for the design and fabrication of equipment for manual installation of the turbine, and for the preparation of an assembly, operation, and maintenance manual (Reference 4).

The contract called for the design, fabrication, testing, and delivery of three prototype machines. Phase I of the contract resulted in an approved design for the 1-kW SWECS (References 1 - 3). The prototypes were fabricated and tested in Phase II. The first of the ASI/Pinson/NPI SWECS was delivered in December of 1979 and the remaining two were delivered by mid-1980 to be tested at the Rocky Flats WSTC.

The overall development program was managed and integrated by Aerospace Systems, Inc., which also provided aerodynamic computer analysis and test planning for the wind energy system. In areas where particular expertise was required, Aerospace Systems, Inc. provided for technical consultation. Pinson Energy Corporation developed the prototype rotor design, fabricated the prototype units and tested the first unit prior to delivery to Rockwell. Natural Power Inc. designed the electrical system using high-reliability electronic technology, and fabricated and tested the prototype units. A block diagram of the program organization showing areas of responsibility is given in Figure 2.

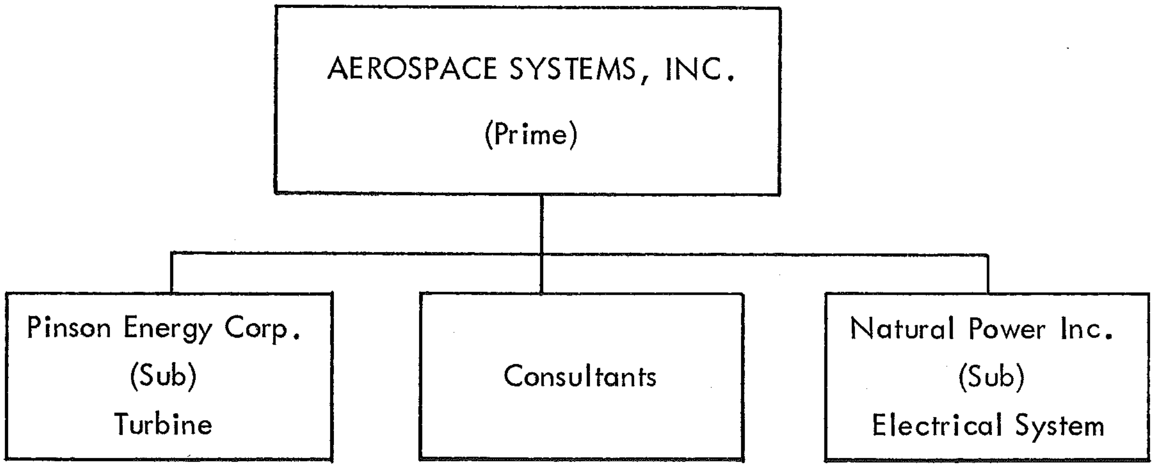
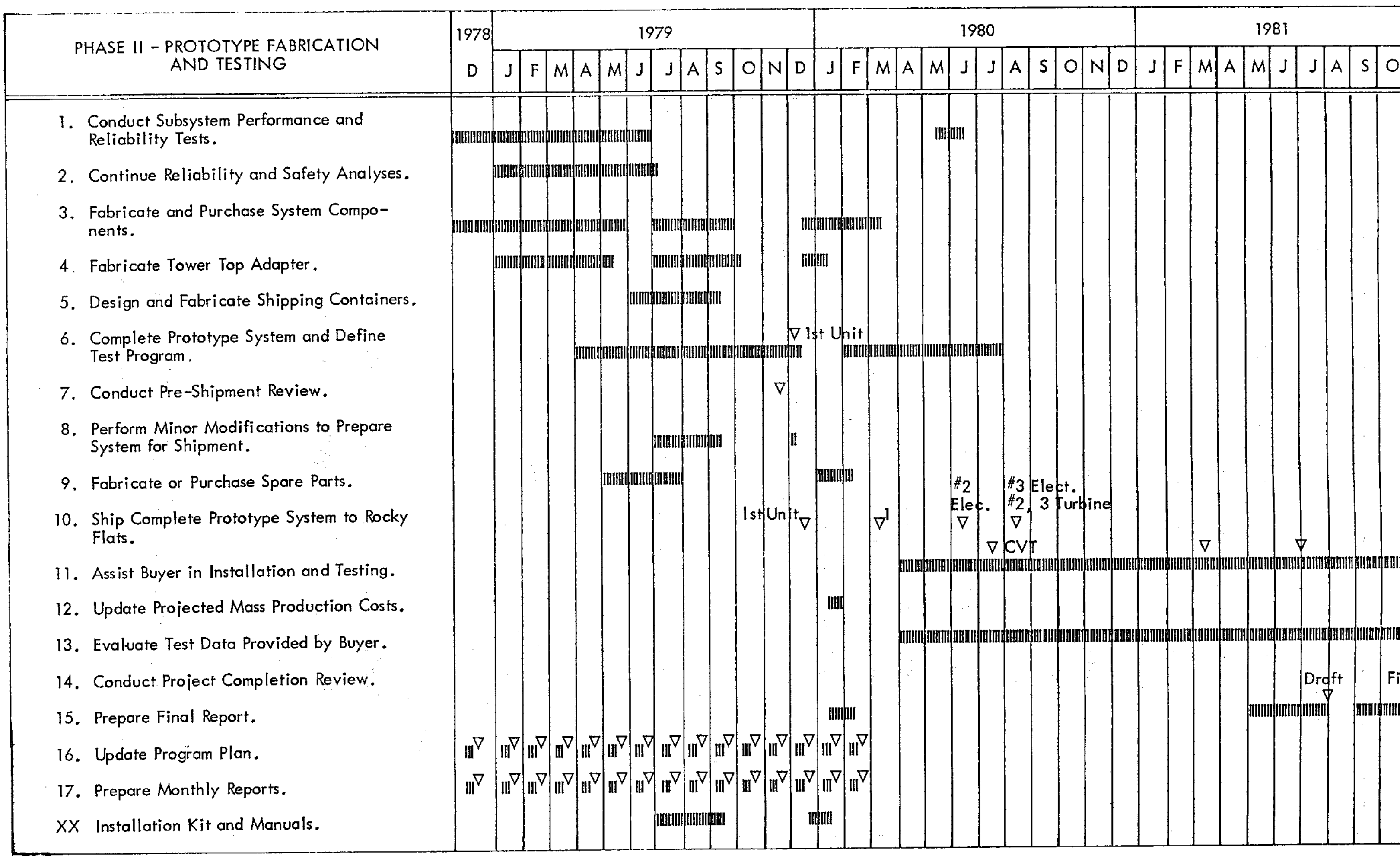



Figure 2. 1-kW High-Reliability SWECS Program Organization.

The fabrication, testing, and delivery in Phase II were conducted by the schedule shown in Figure 3. Significant milestones are indicated in the schedule.

Features of the SWECS delivered to Rockwell during Phase II are summarized in Table 1.

This report begins in Section 2 with an overview of the overall design, fabrication, and testing. Modifications to the design made during Phase II and additional effort approved in Phase II are described in Section 3. Fabrication of the turbine and electrical systems is described and discussed in Section 4. Testing of components, subsystems, and the prototype units is discussed in Section 5. Conclusions relative to the design, development, fabrication, and testing are presented in Section 6. The report concludes with supporting references and appendices.




1 Ship spares, installation kit, #1 trip mechanism

Figure 3. Phase II - Master Schedule for 1-kW High-Reliability SWECS Program.

Table 1. 1-kW High-Reliability SWECS Design Features.

**Turbine:**

- Vertical axis: 15-ft diameter
- Three (3) 8-ft blades
- Swept area: 120 $ft^2$
- NACA-0015 section with 1-ft chord
- Aluminum blades and struts
- Steel main shaft
- Weight: 608 lbs
- $C_p$ of Rotor = 0.4 at 9 m/s
- Start-up velocity: 7 mph
- Shutdown velocity: 30 mph
- Cyclic control
- Aerodynamic/centrifugal shutdown control

**Transmission:**

- 25:1 speed increaser gearbox

**Generator:**

- 1-kW at 2,800 RPM for rated wind speed of 9 m/s
- 24V DC

**Electronics:**

- Voltage regulator and rectifier
- Two (2) transient suppression networks
- Dump load

**Cost:**

- \$1,994 for 1000$^{th}$ unit (1977 dollars)

SECTION 2

OVERVIEW OF DESIGN

## 2.1 DESIGN REQUIREMENTS

The design requirements established for the 1-kW high-reliability SWECS consisted of design specifications and extreme environmental conditions which had to be met. The key design specifications are outlined in Table 2 and the extreme environmental conditions are established in Table 3. Design specifications which were particularly important were reliability and the capital cost goal whereas temperature range and lightning protection were the most important environmental conditions driving the design.

Table 2. Key Design Specifications.

| | |
|---|---|
| Reliability: | MTBF 10 Years Minimum. |
| Maintainability: | One Maintenance Day/Year. |
| Durability: | Continuous Operation in Extreme Weather. |
| Power Output: | 1-2kW at 9 m/s (20 mph) Wind Speed. |
| Power Form: | 26 $\pm$ 2 Volts DC with Voltage Regulation to Control Charging of 24 Volt Battery System. |
| Survival Wind Speed: | Steady Winds 54 m/s (120 mph), Gusts 75 m/s (165 mph). |
| Rotor Speed and Yaw Control: | Optional Design. |
| System Life Goal: | 25 Years. |
| Capital Cost Goal: | $1,500/kW at 9 m/s (20 mph) Wind. |

Table 3. Extreme Environmental Conditions.

| | |
|---|---|
| Temperature: | $-70^{\circ}C$ to $+60^{\circ}C$($-94^{\circ}F$ to $140^{\circ}F$). |
| Rain: | Torrential Downpour with Winds. |
| Snow, Sleet, Icing: | Ice Buildup to 60 mm (2-1/2 in) Thick on Rotor System. |
| Hail: | Impact by Hail up to 40 mm (1-1/2 in) Diameter. |
| Wind: | Steady Wind 54 m/s (120 mph), Gusts 75 m/s (165 mph). |
| Salt Water Spray: | Heavy Ocean Spray. |
| Dust: | Fine Sand and Dust with Wind Gusts to 45 m/s (100 mph). |
| Corrosive Atmosphere: | Heavy Industrial Atmosphere Coupled with Salt Fog or Spray. |
| Lightning: | Repeated Strikes During Severe Thunderstorms. |

NOTE: Values Represent Probable Extremes from Worldwide Applications.

Reliability of the 1-kW SWECS was determined in Phase I in order to verify that the design qualified as a high-reliability machine. The approach used in the reliability analysis by ASI was to determine the probability of nonfailure of the system where failure was defined as excessive wear. Thus, the MTBF defined for the turbine was one in which the machine would continue to function but with parts exceeding wear tolerances, the result of which would eventually lead to degraded performance or failure

Table 4. 1-kW SWECS Reliability

| Assembly | Failures/ $10^6$ Hrs. | MTBF (Yrs.) | One-Year Reliability |
|---|---|---|---|
| Turbine (bearings and structure) | 5.613 | 20.39 | 0.95215 |
| Gearbox (includes coupling) | 0.110 | 1041.17 | 0.99904 |
| Alternator | 0.824 | 138.97 | 0.99283 |
| Electronic circuits (includes dump load) | 4.181 | 27.38 | 0.96413 |
| Tower and foundation | 0.011 | 9999.50 | 0.99990 |
| Total SWECS | 10.739 | 10.66 | 0.91045 |

of a more serious nature. Results for the quantitative reliability analysis based on wear failure data and failure rate estimates are given in Table 4. Evaluation of the reliability of the 1-kW high-reliability SWECS showed that the requirement of MTBF of 10 years (Table 2) was satisfied even when the tower and foundation are included which was not a design requirement. This result was based on wear failure data.

In Phase II, the reliability was to be reevaluated using either empirical data or estimates of failure data of a catastrophic nature. The weld tests (see Section 5.5) were part of this effort. However, the reliability reevaluation was cancelled because of growing program costs.

Manufacturing cost estimates were determined in Phase I for both prototype units and a mass-produced $1000^{th}$ unit. The turbine and electrical system manufacturing costs for the $1000^{th}$ production unit are presented in Table 5. All costs are in 1977 dollars.

Table 5. 1-kW High-Reliability SWECS Cost Elements.

1000$^{th}$ Production Unit

1977 Dollars

| Cost Elements | Cycloturbine | Electrical | Total |
|---|---|---|---|
| Direct Material | $ 720 | $570 | $1,290 |
| Material Overhead (10%) | 72 | 57 | 129 |
| Direct Engineering Labor | 8 | 4 | 12 |
| Engineering Overhead (150%) | 13 | 7 | 20 |
| Direct Manufacturing Labor | 70 | 68 | 138 |
| Manufacturing Overhead (100%) | 70 | 68 | 138 |
| Other Costs | 18 | 16 | 34 |
| Subtotal | $ 971 | $790 | $1,761 |
| General and Administrative Expenses (5%) | 48 | 39 | 87 |
| Subtotal | $1,019 | $829 | $1,848 |
| Profit (8%) | 80 | 66 | 146 |
| Total Price per Unit | $1,099 | $895 | $1,994 |

Costs for production of the first prototype were to be determined during Phase II. All invoicing was identified in accounting procedures, records kept of material and equipment purchased, and labor hours identified for the 1-kW project. However, because of growing program costs, final accounting of manufacturing costs was cancelled.

## 2.2 CONFIGURATION

The 1-kW high-reliability SWECS designed by the ASI team consists of two major subsystems, namely: 1) rotor/transmission; and 2) electrical system.

The physical relationship of the assembled SWECS is shown in Figure 4. The rotor, transmission and the alternator and its transient suppression network are

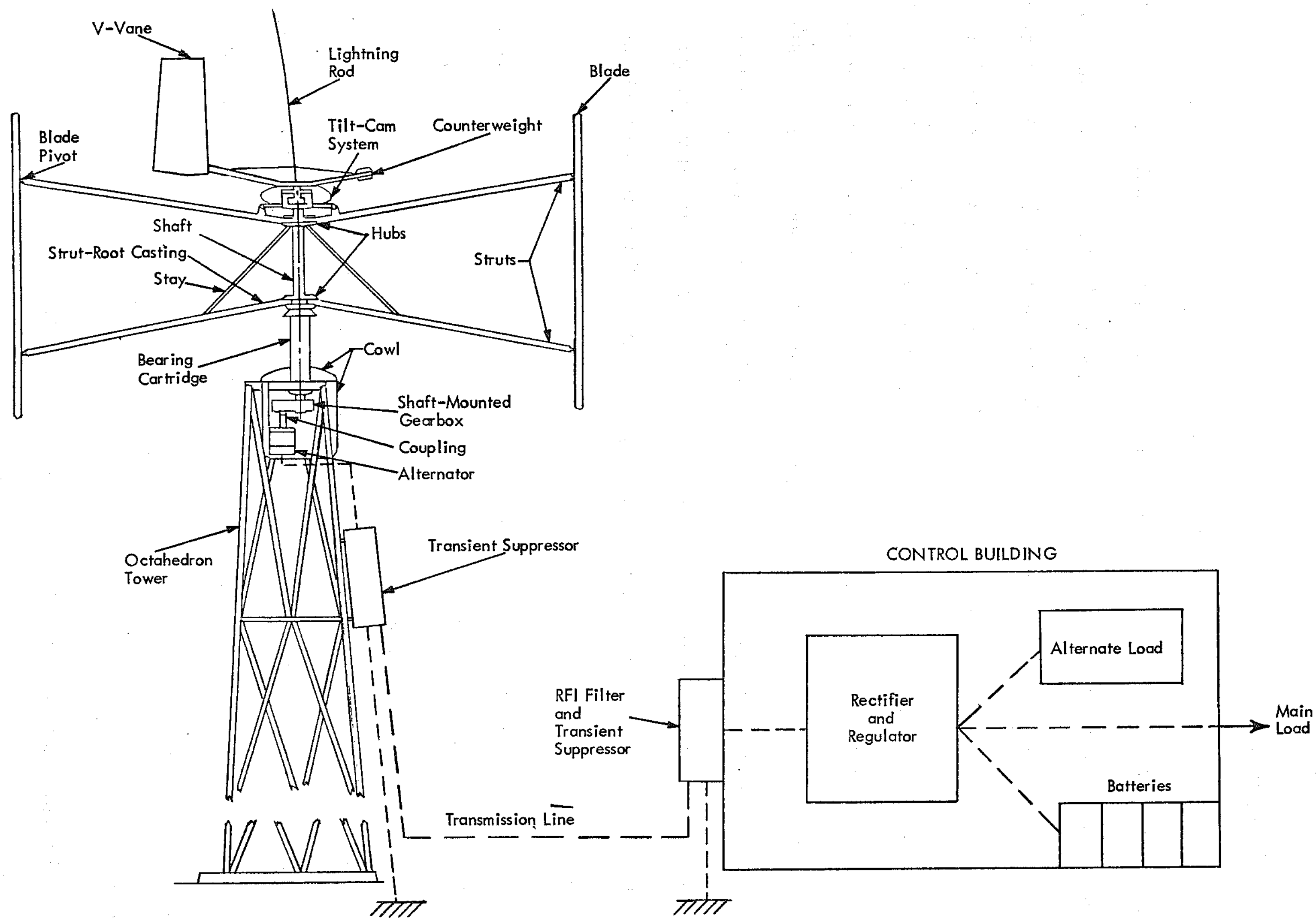



Figure 4. ASI/Pinson/NPI 1-kW SWECS Components.

located on the tower. The remaining electrical components are located in the control building with the batteries.

The turbine has three blades with an NACA-0015 airfoil section set 120 degrees apart on a 7.5 ft radius. The blades extract energy from the wind in the form of aerodynamic loads which cause a torque on the main shaft. The aerodynamic load is controlled by controlling the pitch angle of each blade. Each blade is mounted on two struts which are bolted to twin hub plates welded on the main shaft. A stay passes from the upper hub to the lower strut to provide additional support to resist ice loads.

The main shaft is the central support for the struts and blades. The shaft turns in two flange-mounted ball bearings set in either end of the bearing cartridge. The lower end of the shaft is affixed to the gearbox transmission and the upper end of the shaft houses two cam steady bearings which support the tilt-cam control system. The tilt cam rotates independently of the main shaft. The steel bearing cartridge which houses the main bearings is part of a welded triangular steel structure which bolts to the top of the tower.

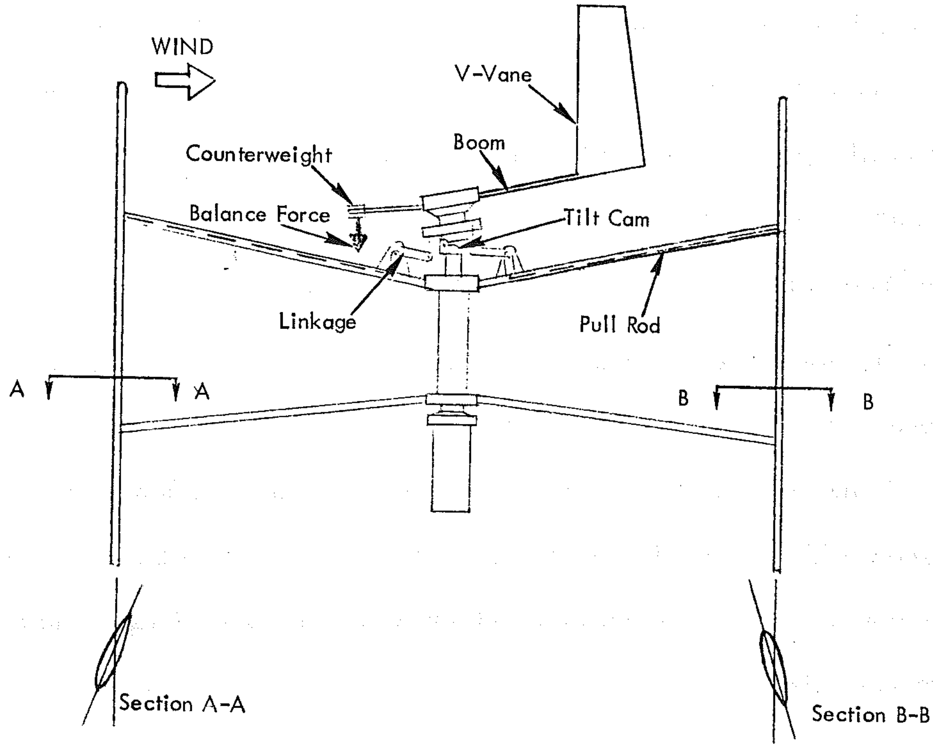
The actuation control system consists of a tilt cam and a series of mechanical linkages which activate pull rods (located in the upper struts) which in turn rotate the blades about their hinge point. The purpose of the control system is to provide a prescribed angle-of-attack, that is, the angle between the blade chord and the relative wind, for each of the blades as they rotate through each cycle. As the main shaft rotates, the tilt-cam mechanism causes the blade position to change. Thus, the tilt cam introduces an eccentricity into the system which acts like a mechanical cam.

The shutdown and restart of the 1-kW high-reliability SWECS is controlled automatically by a mechanical device provided by Pinson. This device, called the trip mechanism, operates in conjunction with the V-vane (see Figure 5). The V-vane assembly provides orientation and shutdown control for the tilt-cam actuation control system. The vane is attached to a boom which, in turn, is rigidly attached to the tilt cam. As the wind changes direction, the aerodynamic loads on the vane cause it to rotate, thereby, reorienting the tilt cam. This action ensures that the blade is properly oriented relative to the wind.

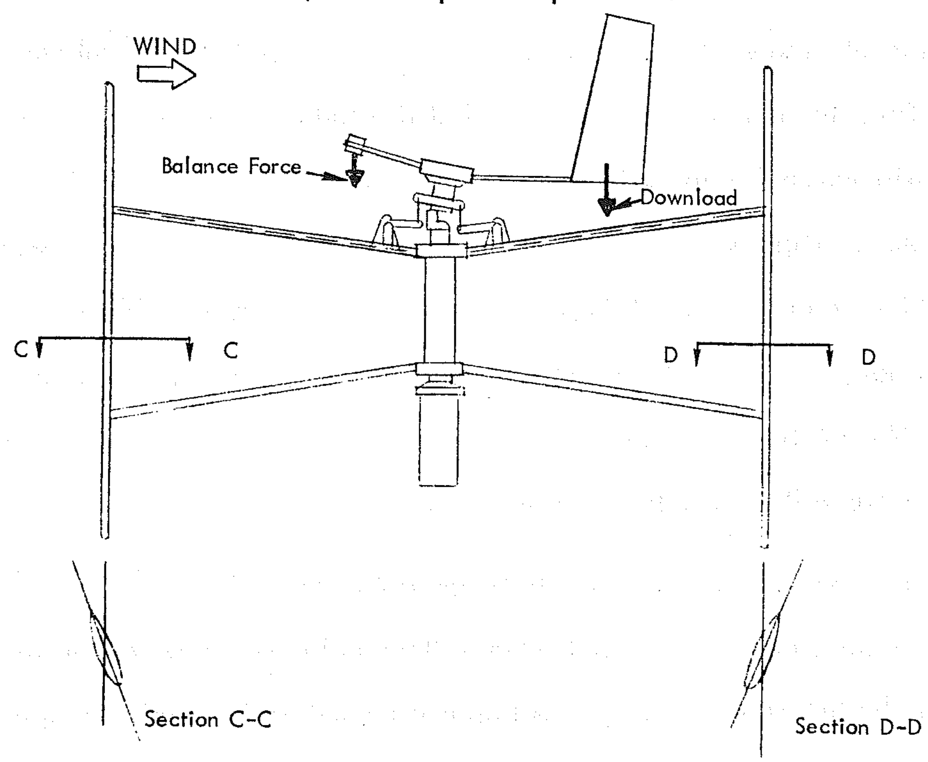
At a rotational speed between 150 and 160 RPM, combined centrifugal and aerodynamic forces cause the automatic shutdown/reset (trip) mechanism located beneath the machine to be set in the shutdown position. This causes the tilt cam angle to decrease which results in a reduction in the blade pitch angles. The effect is to decrease aerodynamic forces on the blades which reduces the torque and causes the turbine to slow down.

The V-vane is designed to produce a download with increasing wind velocity. At a selected wind speed (related to the RPM range), the download on the V-vane offsets the balance weight located at the end of the boom and exerts a force on the trip mechanism through the actuator rod. This force prevents the trip mechanism from resetting to the normal operation position after the centrifugal/aerodynamic load has caused it to shut down the machine in high winds. If the V-vane download was not present, the trip mechanism would reset as the turbine slowed down. If the V-vane becomes heavily loaded with ice, the download on the trip mechanism can cause it to switch to the stop configuration.

The transmission is a commercially-available Morse gearbox with a 25:1 step-up ratio. The gearbox is mounted beneath the bearing cartridge weldment and is driven directly by the main shaft. A coupling is attached to the gearbox output and connects it to the NPI 1-kW alternator. The alternator output is given in Figure 6.




a) Start-Up and Operation.




b) Shutdown (Reverse Pitch).

Figure 5. Schematic of Automatic Control System.

## POWER OUTPUT

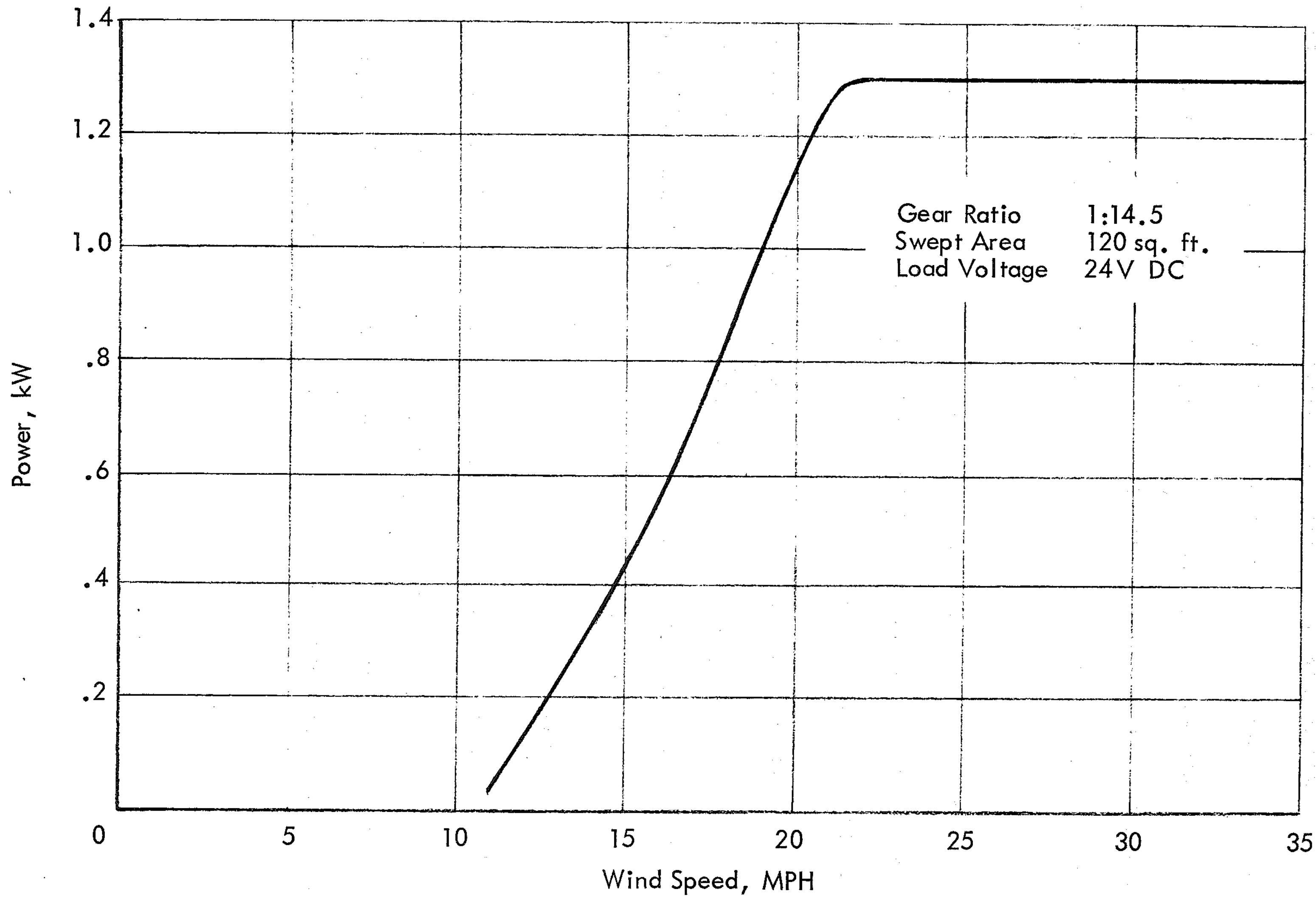



Figure 6. ASI/NPI Alternator Power Output.

The rectifier converts the three-phase AC power from the alternator to direct current and provides the power to excite the alternator field through a separate rectifier. The rectifier is located in the control building to group it with the other semiconductors that need to be protected from low temperature extremes.

The voltage limiter control (or regulator) is designed to regulate the output voltage of the alternator between 24 and 28 volts in the event that the main load or dump load associated with the voltage controlled relay cannot dissipate all the energy available.

The voltage controlled relay circuit (dump load) is used to increase the load on the turbine when the battery becomes fully charged. This unit is set to operate just before the voltage limiter.

The transient suppressors and RFI filters are designed to protect the devices (alternator and the electronic circuitry in the control building) at the transmission line terminations from transient voltages (such as from lightning strikes) and high frequency electromagnetic radiation.

## 2.3 DESIGN CHANGES

During Phase II, a number of changes were made both to the SWECS components and to the overall fabrication/test effort in order to improve the design approved at the Phase I Final Design Review. These changes in the basic design and in the program developed during Phase I are summarized in Table 6.

Table 6. 1-kW High-Reliability SWECS Design Changes.

| Item | Phase I | Phase II | Section |
|---|---|---|---|
| Blade Pivot | External to blade | Internal to blade; lugs welded to leading edge | 3.1.1 |
| Blade/Strut Connection Access | External to blade | Access hole in outer blade surface; cover with aluminum plate | 3.1.1 |
| Blade Balance | Not balanced | Balance required; add balance rod and hardware | 3.1.1 |
| L-link Slots | As designed | Mill additional length | 3.1.2 |
| Strut Tang | As designed | Mill to provide clearance for blade connection | 3.1.2 |
| Strut Tang Bearing | Staked | Peen bearing roll-race | 3.1.2 |
| Blade/Strut Connection | Metallic boot required | No boot required | 3.1.2 |
| Transmission | Morse 15:1 gearbox | Morse 25:1 gearbox | 3.1.3 |
| Gearbox Seals | Standard seals | Low temperature Teflon seals | 3.1.3 |
| Tilt Cam | As designed | Modified to improve cyclic pitch and eliminate collective pitch | 3.1.4.1 |
| Tilt-Cam Bearings | Teflon | Oil-impregnated bronze | 3.1.4.1 |
| Tail Vane | Vertical tail | V-vane | 3.1.4.2 |
| Shutdown Surface | Horizontal wing | V-vane | 3.1.4.2 |

Table 6. 1-kW High-Reliability SWECS Design Changes. (Continued)

| Item | Phase I | Phase II | Section |
|---|---|---|---|
| Vane Boom | As designed | Length added; counterweight increased | 3.1.4.2 |
| Actuator Rod Swivel | As designed | Redesigned to prevent jamming | 3.1.4.2 |
| Trip Mechanism | Not specified; to be mechanical | Device manufactured by Pinson | 3.1.4.2 |
| Lightning Rod | Stainless-steel CB antenna | Reevaluated selection; retained rod | 3.1.5 |
| Alternator | NPI alternator approved; winding not specified | Windings selected using breadboard version; three prototypes built | 3.2.1 |
| Alternator Test | Not specified | Breadboard version had field coil temperature probe; probe not in prototypes | 3.2.1 |
| Induction coils - Alternator Lightning Protection | As designed; commercial units | Handwound to achieve required size | 3.2.2 |
| Lightning Protection Box Bracket | Not specified | Built by NPI | 3.2.2 |
| Dump Load Circuit | Optional | Provided in three prototypes | 3.2.3 |
| Dump Load Relay | High-reliability quality (MIL grade) | Industrial quality | 3.2.3 |
| Software | See Reference 3 | Modify for turbulent wake state and revised inflow | 3.3.1 |
| Installation Kit | Not Required | Design, fabricate and test davit; supply platform, winch, hardware | 3.3.2 |
| Instrumentation | Not required | Install instrumentation, brackets, wires, and connectors; check continuity | 3.3.3 |

Table 6. 1-kW High-Reliability SWECS Design Changes. (Concluded)

| Item | Phase I | Phase II | Section |
|---|---|---|---|
| Manuals | Not required | Prepare assembly, operation, and maintenance manual for turbine, electrical system, tower, and installation kit | 3.3.4 |
| Tower | Recommended 42.5-ft Octahedron | Rockwell purchase recommended tower for testing | 3.3.5 |
| Vibration Tests | Recommended for components and assemblies | Approved by Rockwell; task transferred to Rocky Flats | 3.3.5 |
| Spin Tests | Not planned | Approved by Rockwell | 3.3.5 |

## 2.4 MANUFACTURING PROCESS

The fabrication of the three SWECS prototypes was principally carried out by Pinson and NPI with some work done by contractors. Assistance was provided by ASI in the final assembly of the first prototype turbine.

Fabrication was done using standard manufacturing processes such as cutting, drilling, milling, machining, soldering, welding, riveting, painting, etc. Each prototype was hand built. In addition, for the electrical system, induction coils for the alternator lightning protection system, and field and output coils for the alternators were hand wound. PC boards and back panels were made in-house. Other components were commercially available. For the turbine, all components were fabricated in-house except for bearings, extrusions, gearbox, gearbox/alternator coupling, and instrumentation.

The following manufacturing processes were supplied by subcontractors:

Electrical System

Painting

Turbine

- Casting
- Extruding
- Bending
- Welding (available in-house after September 1979)
- Centerless Grinding
- Galvanizing
- Heat treating
- Anodizing
- Fiberglass Molding
- Painting (Logo only)

## 2.5 TESTING

Considerable effort in Phase II was directed toward the testing of components, subassemblies, and the prototype systems. Performance results from the prototype system indicated a power output of 940 watts at 20 MPH, and 1.4 kW at 25 MPH. The system power coefficient was determined to be 0.25. The major tests, their objectives and results are summarized in Table 7.

Table 7. Summary of Phase II Tests

| Test | Test Period | Objective | Result | Section |
|---|---|---|---|---|
| COMPONENT: | | | | |
| Test Machine I | Jan. 1-10, 1979 | Determine operation of tilt cam; checkout prototype strut manufacture, assembly, operation. | Tilt cam modified to provide increased pitch range; strut acceptable; machine damaged in storm (blades damaged) | 5.2.1 |
| Test Machine II | March 3-June 1, 1979 | Determine operation of tilt cam; checkout prototype blade manufacture, assembly, operation | Tilt cam modified to eliminate collective pitch; blade acceptable but problems with leading edge extrusion twisting | 5.2.1 |
| Wing | Jan.17-24, 1979 | Obtain $C_L$ characteristics of horizontal wing | $C_L$ characteristics determined | 5.2.3 |
| V-Vane | Oct.10-12, 1979 | Obtain $C_L$ characteristics of V-vane | $C_L$ characteristics determined | 5.2.4 |
| Breadboard Alternator | Feb. 1979 | Determine output vs RPM of breadboard alternator for various output coils | Output vs RPM characteristics determined; select 9 turns per output coil for prototype | 5.3.1 |
| Prototype Alternator | Aug.10, 1979 | Verify output vs RPM of prototype alternator | Proper functioning verified | 5.3.2 |
| Davit | May 26, 1979 | Conduct manual installation of prototype turbine with Pinson davit | Davit failed; design new davit | 5.4 |

Table 7. Summary of Phase II Tests (Continued)

| Test | Test Period | Objective | Result | Section |
|---|---|---|---|---|
| Davit (continued) | June 30, 1979 | Conduct hoist test with prototype aluminum davit | Davit failed due to improper welding; redesign davit. | 5.4 |
| | Aug.24, 1979 | Conduct hoist test with revised davit (steel) | Test load hoisted; redesign crane. | 5.4 |
| | Sept.7, 1979 | Conduct hoist test with revised prototype aluminum davit | Test load hoisted successfully; davit acceptable. | 5.4 |
| SUBASSEMBLY: | | | | |
| Breadboard electrical system electronics | Jan. 1979 | Burn-in of components | Components and circuits satisfactory | 5.3.1 |
| Breadboard electrical system | Feb. 1979 | Determine system characteristics and output | System performed as designed; alternator design selected. | 5.3.1 |
| Turbine | Sept.13-Oct.19, 1979 | Spin tests of prototype to determine control forces and checkout operation of trip mechanism | Control forces remained in one direction - of proper magnitude; trip mechanism operates correctly - required adjustment; blades required balancing to eliminate 1-per-rev oscillation. | 5.2.5 |

Table 7. Summary of Phase II Tests (Concluded).

| Test | Test Period | Operation | Result | Section |
|---|---|---|---|---|
| PROTOTYPE SYSTEM: | | | | |
| Series I | June 1-July 24, 1979 | Checkout assembly and operation of prototype turbine; checkout operation of breadboard electrical system | Turbine operated smoothly; start-up in winds of 5-7 MPH; turbine stopped slowly; 940 watts output at 20 MPH; system $C_p = 0.25$; control force reversed - blade modification required; electrical system failed - bad diode due to improper removal of fuse | 5.2.2.1 |
| Series II | Aug. 1-21, 1979 | Checkout modified blades; checkout operation of prototype electrical system (breadboard alternator used) | Proper control forces obtained; startup sluggish; forces on horizontal wing appeared low - replace with V-vane | 5.2.2.2 |
| Series III | Oct. 29-Nov. 19, 1979 | Checkout operation of V-vane with Pinson trip mechanism; checkout operation of prototype electrical system | V-vane adjusted by adding more counterweight; V-vane buffeted in high winds; trip mechanism worked in moderate wind - final adjustment not obtained; startup sluggish; checkout of electrical system not accomplished. | 5.2.2.3 |

# SECTION 3

# DESIGN CHANGES

During Phase II, a number of changes were made both to the machine components and to the overall fabrication/test effort in order to improve the design approved at the Phase I Final Design Review. These changes in the basic design developed during Phase I are discussed in this section and were summarized in Table 6.

## 3.1 TURBINE

### 3.1.1 BLADES

Initial tests of the prototype machine on a tower revealed a control system problem. The control force data showed that the actuator rod force could be either tensile or compressive which was unacceptable for operation of the proposed automatic shutdown and restart system. Considerable time was spent evaluating the control force reversal to determine its effect on the machine operation. It was determined that the problem was largely due to the offset of the blade pivot point from the CG of the blade. It was decided that new blades would be designed and fabricated with the pivot as close to the CG as practical.

A new set of blades was designed. The blade pivot was moved internal to the blade so that the pivot lay on the chord line about 1/4-in. aft of the CG. This was to preclude the inertial forces from causing a compressive load on the actuator rod system. The leading-edge extrusion was modified by welding tabs on it to accept the strut tang. Welding of these tabs proved to be a problem in terms of the test schedule since it took several weeks to get the extrusion returned. In order to meet the test schedule, it was decided to assemble the blades without having the leading edges heat treated and anodized. The skins of the prototype blades were removed and riveted to the new leading edges. The tabs and the pull rod lug welded to the leading-edge extrusion are shown in Figure 7.

Assembly of the blade to the struts was now tedious because the attachment point was internal to the blade. A single bolt acted as the attachment and hinge as in the original design (see Figure 3-13, Reference 2). In order to provide access to the attachment, access ports were cut in the outboard surface of the blades as shown in Figure 8. These ports were covered with an aluminum plate mounted internal to the afterbody skin (see Figure 9). The cover was riveted on one side (see upper fastener, Figure 9) to allow it to be rotated to one side to allow access to the attachment. When rotated to cover the ports, a screw was used to hold the cover in place (see lower fastener, Figure 9).

A mass unbalance in the blades which resulted in a 1-per-rev oscillation was detected during spin tests (see Section 5.2.5). The blades were removed from the machine and their balance checked. Each blade was suspended from its strut connection points. These points had been checked and found to be within established tolerances. Any corrective moment required to attain a level condition was achieved by applying a force at the pull rod connection. The force was measured on a small scale. All of the blades were found to be out of balance. In addition, all three blades had different weights.

To correct the mass unbalance, a hole was drilled in the leading edge of each blade about one foot from the top. A threaded 5/16-in. rod was inserted in the leading edge, passing through the spar section, and ending near the trailing edge. The rod extended forward of the leading edge about 4 inches (see Figure 10). As the rod was inserted into the blade, nuts and washers were placed on it fore and aft of the C-spar section (see Figure 11). Sufficient nuts and washers were used so that each blade had the same weight. The balance was rechecked. If unbalance was noted, the nuts were moved on the rod until balance was achieved.

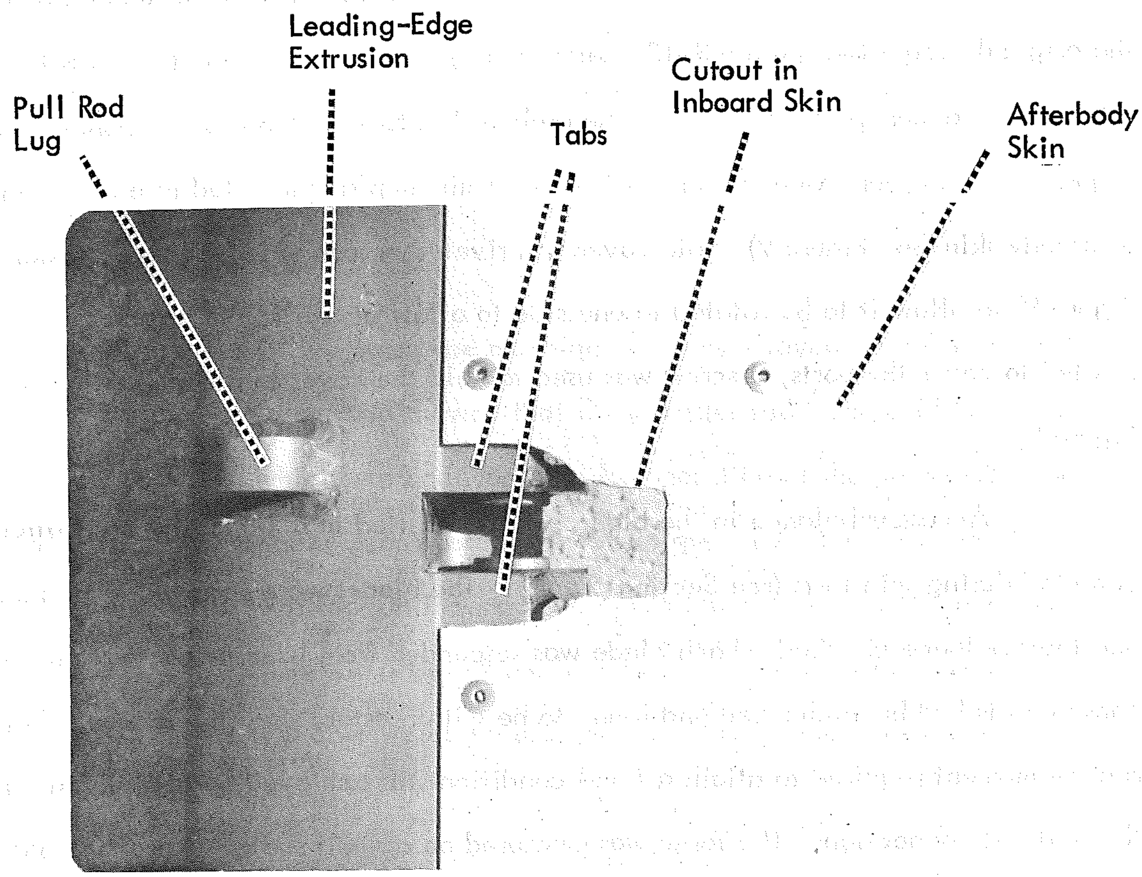



Figure 7. Lugs with Washers on Leading-Edge Extrusion for Blade/Strut Connection; Also Pull Rod Lug.

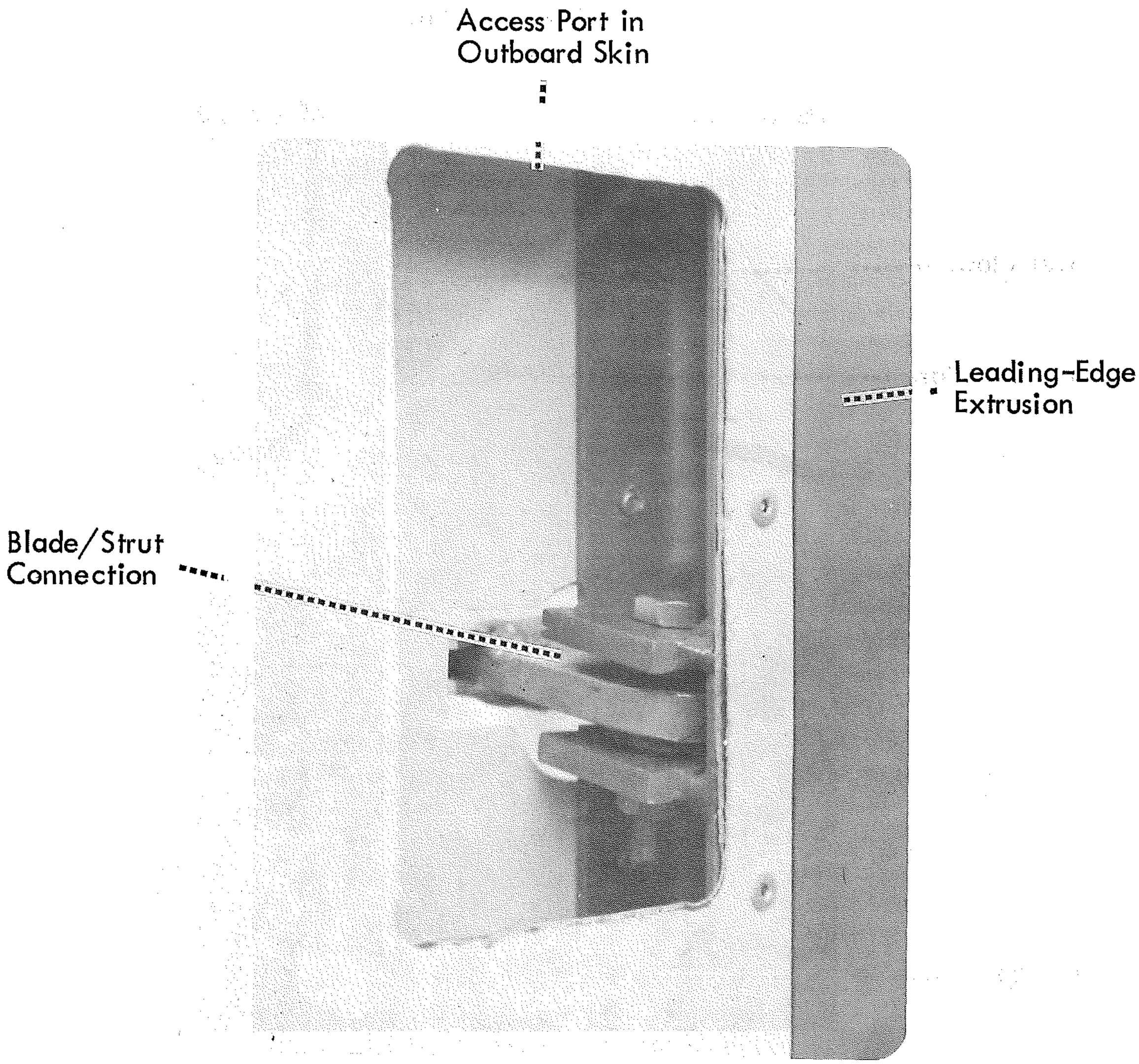



Figure 8. Blade/Strut Connection Viewed Through Outer Surface Opening.

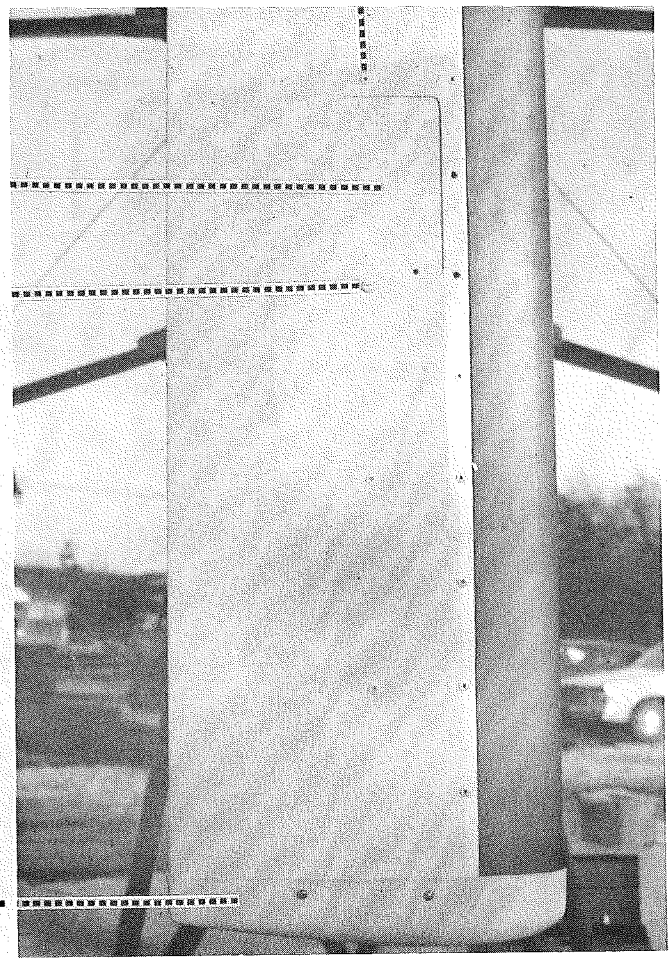



Figure 9. Lower End of Blade Showing Access Cover in Place and End Cap.

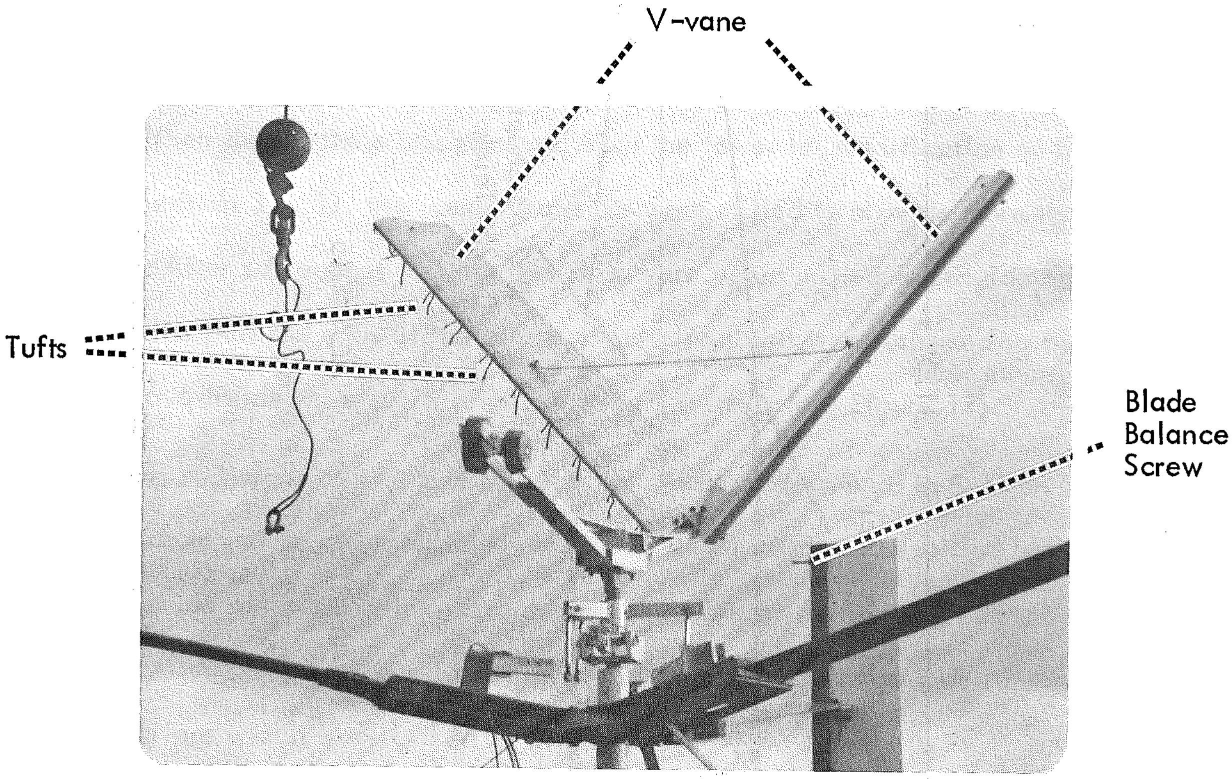
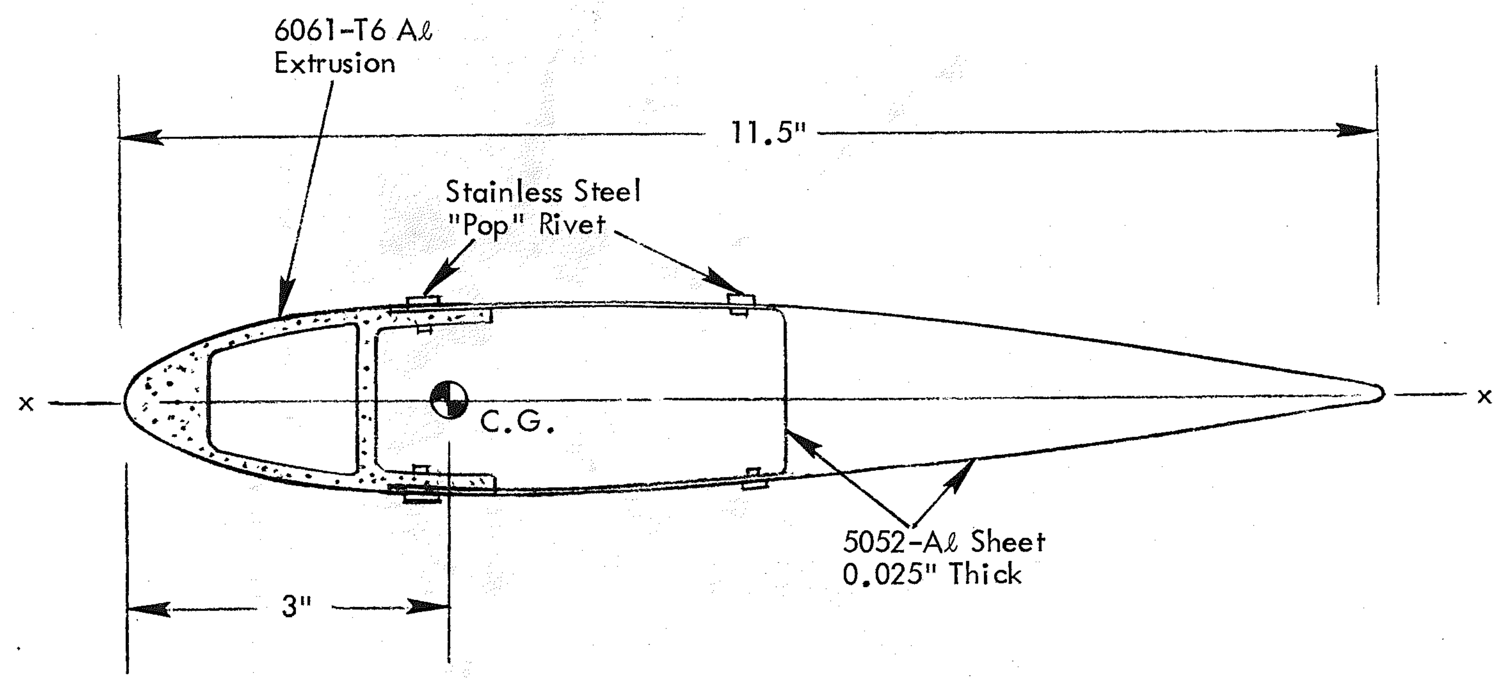



Figure 10. View of Turbine Showing Blade Balance Rod and Tufts on V-vane.




Airfoil Section: NACA 0015

$I_{xx} = 0.67 \text{ in}^4$

Figure 11. Blade Construction.

It was also proposed that the balance hardware on the blades be replaced with stainless steel hardware. However, it was decided not to do this in order to avoid the necessity of rebalancing the blades on the first prototype. The hardware used was cadmium plated.

### 3.1.2 STRUTS

Testing of the first prototype on the tower revealed that the control system L-links required more room in the slots in the struts and that the pull rods were hitting the struts. When the machine was removed from the tower for modification of the blades (see Section 3.1.1), the upper strut slots were milled to provide more throw for the L-links. After subsequent testing, the slots were again milled to provide additional clearance. The pull rod ends at the blade connection point were shimmed so that the rods could move inside the struts without striking the struts (see Figure 12).

The redesign of the blade/strut connection was described in Section 3.1.1. In order to accommodate the internal connection, the strut tang was milled both fore and aft to provide clearance where it entered the blades at the leading edge. This modification, however, weakened the tang. In addition, Pinson provided information that tang bearings which were staked in the tangs had worked loose in the tangs in some field installations. These bearings were subsequently replaced with a modified bearing installation.

It was recommended by ASI and Pinson that the strut tangs be redesigned and that the modified bearing installation be used on all struts. Replacement of the tangs would necessitate removing the old tang by cutting it out and then welding the new tang in place. This would cause local annealing of the metal so that the entire strut assembly would have to be reheat-treated and reanodized. This could be readily accomplished on five of the struts but the sixth strut was already instrumented with strain

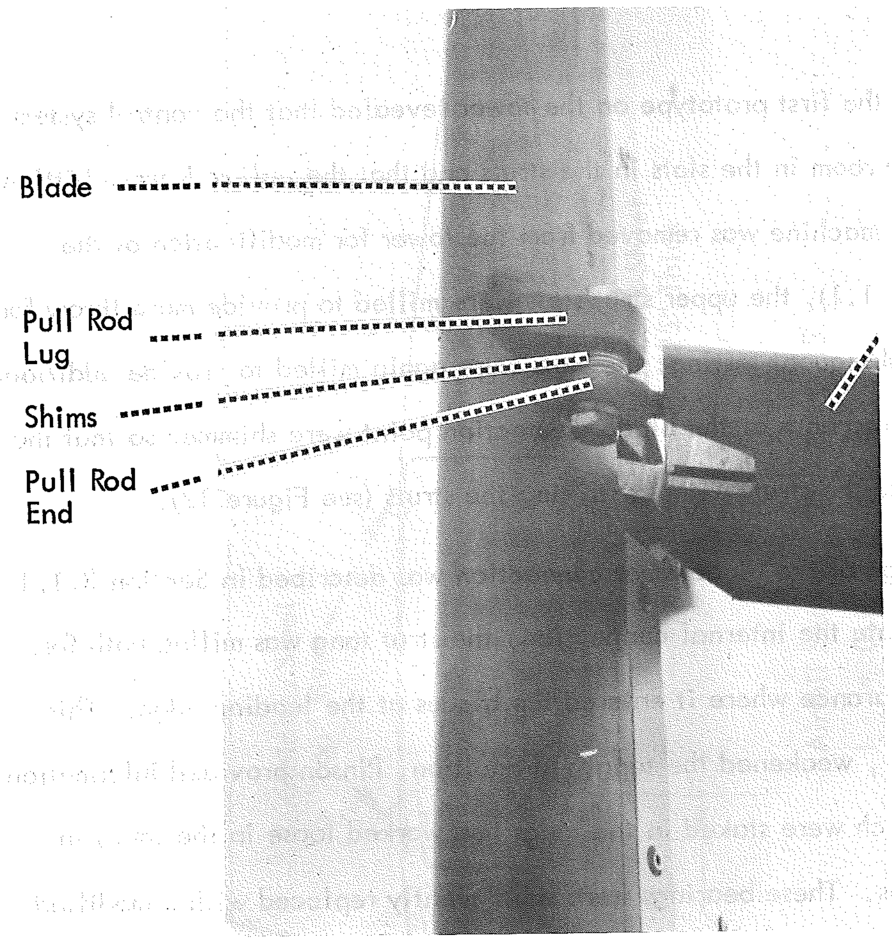



Figure 12. Pull Rod Connection to Blade.

gauges. The gauges could be easily damaged by the above process. Therefore, it was decided by ASI to retain the original tang/bearing design but recommend that the new design be incorporated in the second and third prototypes. It was noted that replacement of the tang/bearing on the first prototype would have resulted in additional schedule delays. The tangs for the second and third prototype turbines were of the same basic shape as that of the first prototype, but was of the thickness of the spherical bearing ball rather than that of the race. Also, the bearing was held in place by using circular peening of the bearing race rather than staking the tang.

The modified blade/strut connection appeared to be aerodynamically cleaner than the original design inasmuch as the connection was now internal to the blade. Therefore, the metallic boot proposed at the Phase I Final Design Review for the connection was deleted.

### 3.1.3 TRANSMISSION

A Morse 115D15 shaft-mounted, double reduction speed reducer used as a speed increaser had been selected as the transmission. However, reevaluation of the basic design indicated that the electrical system would be enhanced if the alternator would be turned at a faster speed than originally proposed. Therefore, the possibility arose of the need for a 25:1 gearbox ratio. It was determined that the 15:1 and 25:1 gearboxes have the same physical size. It was learned that a 25:1 gearbox modified for vertical running would take several months for delivery whereas one not modified for vertical running was available immediately. Therefore, the Morse 115D25 (25:1) gearbox was ordered in addition to a vertical-running 15:1 gearbox previously ordered. The seals and grease fitting designed for the vertical-running 15:1 gearbox were removed and installed in the 25:1 gearbox. A special grease manufactured by Dow Corning, known as Molycoat, is used for the gearbox bearings. Being silicone based, it is capable of retaining lubricational values to $-100^{\circ}$F.

The seals provided with the gearbox did not meet the low-temperature requirement. It was determined from Morse, the gearbox manufacturer, that special low-temperature seals they provide are known to be effective to -80°F although they suspect that the seals could operate at -94°F. However, Morse quoted a 50-week lead time. It was then learned that Maremont Corporation, basic manufacturer of the NPI alternator, could put Teflon seals in the gearbox which would meet the temperature specification. In addition, Maremont could test the unit to -100°F.

The low-temperature seals were ordered from Maremont. These special graphite-filled Teflon seals are of the double-lip type, which permit the Morse gearbox to operate in a vertical position. Maremont noted that these seals have been used in cryogenic applications, and that the 1-kW requirement of -94°F would be nothing out of the ordinary. Low temperature tests of the gearbox with the special seals were deemed unnecessary. Cost of these seals for the three prototype units was about $1,200. The three prototype gearboxes were delivered with standard seals.

Since the gearbox is to be run at high speeds at certain times, an aircraft-type oil temperature gauge was installed in the gearbox to monitor the oil temperature during testing. Power for the gauge was supplied by a small 12 V DC motorcycle battery.

### 3.1.4 CONTROL SYSTEM

#### 3.1.4.1 PITCH ACTUATION SYSTEM

The cyclic pitch schedule of the blades is controlled by the tilt-cam system (Figure 4). The original tilt-cam design was modified after initial testing (see Section 5.2.1) to allow for increased blade pitch angles. Subsequent tests uncovered a problem in achieving self-starting. Reevaluation of the tilt-cam design revealed that the kinematics of the tilt cam were producing the desired cyclic pitch schedule, but were inducing an undesirable collective pitch angle which inhibited the self-start capability of the machine. As a result, the tilt-cam design was modified to reduce this undesirable effect.

During subsequent testing of the prototype machine on the tower, the main hinge bolt in the tilt cam bent. Additional support was added to prevent it from bending. Inspection of the tilt cam following spin tests revealed excessive slop in the system. It was found to be necessary to replace some of the Teflon washers with oil-impregnated bronze in order to eliminate slop in the mechanism.

### 3.1.4.2 AUTOMATIC SHUTDOWN/RESTART SYSTEM

The automatic shutdown/restart system consists of the vane/boom mounted above the tilt cam (see Figure 4); the actuator rod which transmits control forces to the shutdown mechanism; a swivel at the lower end of the actuator rod which allows the rod to turn while swivel remains stationary; and the shutdown mechanism. The shutdown mechanism, referred to as a trip mechanism herein, is a device manufactured by Pinson.

The vane/boom design approved at the Phase I Final Design Review consisted of a vertical tail for tilt cam orientation, a horizontal wing as part of the shutdown/restart system, and the mounting boom. Limited results from prototype machine tests indicated that the horizontal wing on the tail boom was not producing the expected download on the tilt-cam system. It was determined qualitatively that the velocity of the airflow inside the turbine was noticeably slower than the wind speed. Although it was planned to measure the airflow velocity near the wing, it was not possible because of the poor wind conditions during the scheduled test period. As a result of the limited findings, the original tail vane/wing system was replaced with a V-tail configuration shown in Figure 13. The new vane was checked out in the spin tests (see Section 5.2.5).

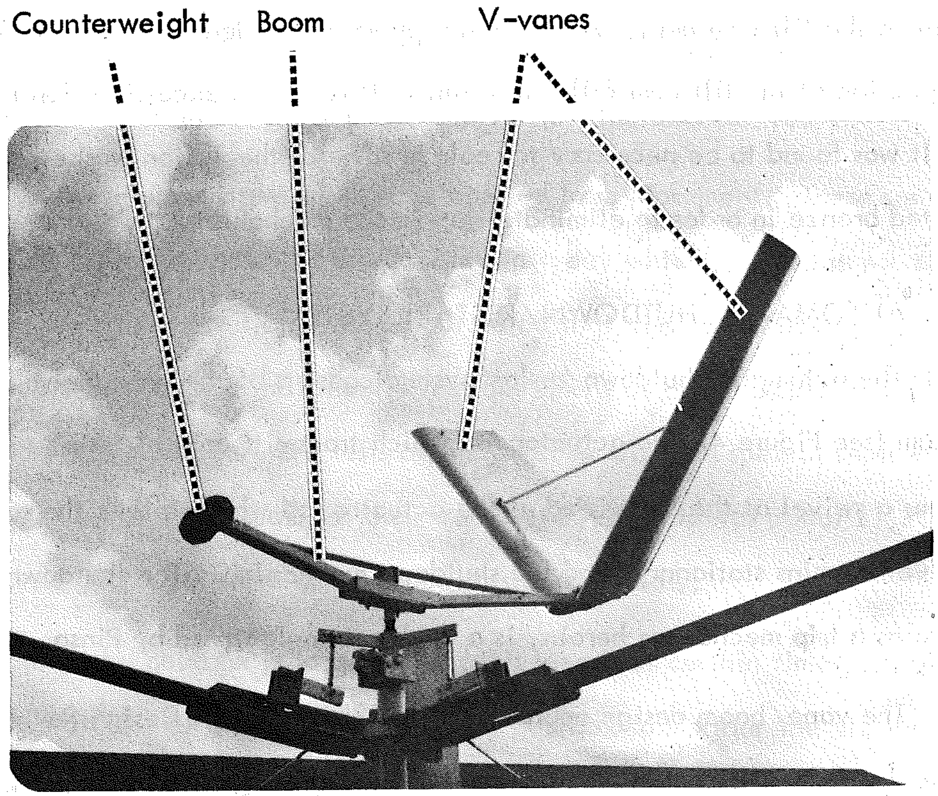



Figure 13. V-Tail Configuration.

In order for the V-vane to control the shutdown and restart of the turbine in conjunction with the trip mechanism, the aerodynamic force produced on the V-vane must be partially offset by a counterweight (see Figure 5). As a result of the spin tests, it was determined that a relatively large weight was required to produce the desired offsetting moment. The desired moment was achieved by a combination of adding weight as well as extending the length of the boom so that the weight would act through a longer moment arm. Fifteen pounds of weight were used as the counterweight for the initial tower tests.

Inspection of the shutdown/restart system following spin tests revealed that the actuator rod swivel at the strain-gauged force beam had jammed. A new swivel was designed and fabricated to prevent jamming. Also, an extension was added to the actuator rod to permit mounting of the linear transducer (see Section 3.3.3).

Several trip mechanism designs were available from Pinson, all of which could fit in the space below the alternator. All worked on the principle of limiting centrifugal forces through a spring arrangement. Each mechanism required that the tilt-cam system be subjected to down loads only, that is, the pull rods were always in tension. Final design required the selection of the appropriate spring forces; however, control forces measured on the first prototype indicated that the pull rods were also being loaded in compression which necessitated redesign of the blades (see Section 3.1.1). One of the trip mechanisms was tested during the spin tests (see Section 5.2.5). This trip mechanism was installed on the prototype machine during the final series of tower tests (see Section 5.2.2).

Prior to delivery of the first prototype, Pinson offered a new trip mechanism which had been developed for their commercial machine designs. It also required that the pull rods remain in tension, but it was simpler using a weighted rotating beam actuated through a lever connected to the actuator rod rather than using calibrated springs. In addition, it was more convenient to mount, being located low on the tower rather than beneath the gearbox. The device is described in Section 4.1.7.

The design of the new trip mechanism was such that adjustment of the blade pitch angles was still done beneath the machine but adjustment of the shutdown and reset speeds could be done on the ground. The adjustments were readily accomplished whereas adjustments were very awkward to make on the previous design. Therefore, it was decided by ASI to use the new trip mechanism which operated on the same principle as the first prototype version but which afforded more space beneath the gearbox, and which did not interfere with the instrumentation.

### 3.1.5 LIGHTNING PROTECTION

Lightning protection for the turbine was reevaluated. This system consisted of an 8-ft stainless steel antenna mounted on the V-vane boom as a lightning rod. This was the design submitted and approved at the Phase I Final Design Review. The possibility of using a larger diameter rod and a positive ground wire were considered during completion of the turbine. It was determined that a No. 4 AWG wire was required. Although a braided wire could be run to provide a positive path past tilt-cam bearings, wire could not be passed internal to the main shaft. Most probably, a direct strike on the turbine would melt the tilt-cam ground wire onto the mechanism with subsequent deleterious results. Suggestions provided to ASI by General Electric (Reference 2) indicated that even if a ground wire could be run through the machine, the high inductance surge produced by a direct strike would select a path which would pass through the main bearings. Only a costly redesign could provide a path around the bearings, and this could not be guaranteed. The suggestion by General Electric was that the most feasible solution was to install a lightning rod which would provide a cone of protection for the blades, the component which, in their opinion, would be most susceptible to extensive damage. Therefore, as a result of considering what can be done in a practical manner and a reconsideration of the recommendations by General Electric, it was decided not to modify the existing protection system. Although the rod itself may prove to be light, it can be readily replaced if it encounters significant damage.

## 3.2 ELECTRICAL SYSTEM

### 3.2.1 ALTERNATOR

The NPI alternator approved at the Phase I Final Design Review was a proposed modification based on an existing version of the alternator. In order to verify the actual output of the proposed alternator, a preliminary model ("breadboard") was constructed and tested (see Section 5.3.1). The breadboard alternator was wound with 10 turns of AWG 12 copper wire on its output coils. Test results from this alternator indicated it would be desirable to reduce the slope of the output curve to obtain a better match to the power available from the turbine.

A second alternator was wound with 11 turns of AWG 12 wire and a similar field coil. This version did not produce the desired results. Therefore, a third breadboard alternator was constructed, this time using 9 turns of AWG 12 copper wire. Satisfactory test results were obtained. This breadboard alternator was used for most of the prototype testing (see Section 5.2.2) and formed the basis of the prototype alternator. Primary difference between the breadboard and prototype alternator was that the prototype field coil was wound without a temperature probe whereas one had been incorporated in the breadboard unit.

### 3.2.2 TRANSIENT SUPPRESSION

Tests of the alternator lightning protection network (subassembly A1A2) revealed that the series induction coils overheated. These coils were replaced with hand wound units fabricated by NPI. The coils were increased in size until a size was achieved which did not overheat.

It was decided that the lightning protection circuit for the alternator should be mounted on the tower below the machine. The bracket to mount the cabinet on the tower was fabricated by NPI. The bracket was made of steel and galvanized for corrosion protection.

### 3.2.3 VOLTAGE CONTROLLED RELAY

The voltage controlled relay, or dump load (subassembly A2A2) was included as part of the electrical system at the Phase I Final Design Review. Subsequently, as part of an effort to reduce prototype cost, the dump load was included as an option only. However, fabrication of the first prototype included the dump load. Prior to construction of the last two prototypes, the dump load option was reevaluated to determine if it should be deleted from the first prototype or included in the last two.

The cost and the need of the dump load circuit were reviewed by NPI and ASI. It was recommended that the dump load be incorporated in all three prototypes to enhance the operational versatility of the turbine. Although the dump load had little effect on the system reliability, it was felt that it would reduce cycling in the charging system. Fault tree analysis of the dump load was not conducted. Although a cheaper relay could be used (the high-reliability version then cost about $165), it was decided to use the high-reliability version. Rockwell concurred that the dump load should be used on all three prototypes.

The electrical system subsequently was modified by replacing the dump load control relay with the less expensive version. The high-reliability relay cost about

$165 whereas the replacement relay cost about $35. Although the new relay was less reliable, it was not expected to seriously impact the overall reliability because of the nature of the circuit design. The relay in the first prototype was replaced with the less expensive version.

## 3.3 RELATED EFFORT

### 3.3.1 SOFTWARE

Calculations made for the turbine with a tilt-cam system resulted in values of the power coefficient that seemed unreasonable. A detailed review was made of the performance analysis to determine the cause of the difficulty. It was learned that the problem occurred for a collective pitch angle, $\theta_o$, of zero and when cyclic pitch angles, $\theta_{1_c}$ approached zero. For turbine solidities in the neighborhood of 0.17, it was determined that the pitch angles caused the calculated inflow to become negative; that is, it became an outflow. This theoretical condition was indicative of a rotor operating in the turbulent wake state, in which case the analysis used for normal wind machine operations does not apply.

Checks were put into the program for the ratio of the inflow velocity to the wind speed and for specified ranges, modifications were made to the mean inflow, $\lambda_o$, calculation and to the calculation of the cyclic inflow, $\lambda_{1_c}$. These modifications were semiempirical, based on data available for similar flow conditions for helicopter rotors. A cyclic inflow parameter, $K_{1_c}$ with a value of 0.5 was used for computation. With this value, the inflow velocity upwind is 0.5 $v_o$ and down wind is 1.5 $v_o$, whereas, it is $v_o$ at the turbine center plane.

The tilt-cam control system was designed to control the cyclic pitch schedule of the blades with little or no collective pitch. It had been determined from previous experience by Pinson that collective pitch was not necessary for effective control of the turbine performance. It was also felt that cyclic pitch angles of about 10 degrees were necessary for the test performance of the machine. The revised computer analysis of the 1-kW high-reliability SWECS performance was conducted to determine the effect of various collective and cyclic pitch angles on the performance. These results indicated that a cyclic pitch angle of between 4 and 6 degrees appears to be the optimum regardless of any collective pitch angle.

### 3.3.2 INSTALLATION KIT

The installation kit consists of a davit for manually installing the machine, a winch for hoisting the machine, a platform used for working on the machine while it is mounted on the tower, and associated cables, pulleys, ropes, and hardware. It was originally intended to supply a davit used by Pinson in the installation of their commercial machines. However, tests with this equipment showed that it did not have sufficient strength to hoist the present machine. A new design was offered which was a crane-type boom mounted to the tower. The basically aluminum structure was fabricated by Thompson Engineering (see Section 5.4). The new davit was designed to permit installation of the completely assembled 1-kW turbine rather than just the weldment and main shaft. Although the davit was sufficiently strong to lift the weight, it tended to rotate and, as it did so, the change in loads caused the davit to fail at the joint which had been incorrectly assembled.

A steel davit was fabricated to incorporate changes recommended as a result of the test conducted on the previous version. This davit, which was considered to be a prototype for an aluminum version, had a nonrotating crane, stays and guy wire on three sides to increase stiffness (see Section 5.4). The davit was tested and found to be satisfactory. The aluminum prototype was completed and tested (see Section 5.4). One of the steel cables which provided tension support to the davit boom was overstressed and parted. The failure was due to a defective Crosby cable clamp which was replaced. The prototype davit was subsequently used by Pinson to install several commercial units, verifying the adequacy of the design.

The platform was based on a version used by Pinson for commercial operations. It consists of an aluminum frame with a plywood floor. The unit can be hoisted into position on the tower using ropes and pulleys.

A winch was supplied which can be operated either manually or electrically from an automobile battery. The manual mode is useful for remote installations.

### 3.3.3 INSTRUMENTATION

Modifications were approved to add test instrumentation to the first prototype. This required planning and revisions for instrumentation location, wiring diagrams, component selection, and ordering, selection of wiring paths in the structure, and determination of calibration techniques. Equipment included instrumentation, wiring, connectors, and mounting brackets. Quantities to be measured included shaft torque, shaft RPM, tilt-cam angle, tilt-cam force, wind vane angle, and blade azimuth position. Although strain-gauge measurements were desirable, they were not initially included because of lack of suitable slip rings. Subsequently, slip rings were developed by Wendon for Rockwell and strain-gauge measurements were specified. As a result, torque was to be measured by a strain-gauge rosette on the main shaft instead of by calibration of electrical outputs, and stress measurements on the struts and blades were included. The strain-gauge rosette was later replaced by a strain-gauge torque link for the gearbox. Also, measurement of tilt-cam force by a load cell mounted beneath the gearbox was replaced by a strain-gauge on an L-link in the control system to measure pull-rod force. Initially all strain-gauge calibrations were to be done by ASI/Pinson; however, this task was subsequently transferred to Rockwell in accordance with a revised policy instituted to ensure consistency in the testing of all wind machines at Rocky Flats.

The following instrumentation was included on the first prototype:

Long-Term Testing

- RPM - Trump-Ross shaft encoder.
- V-Vane Azimuth Position - Rotary potentiometer.
- Tilt-Cam Angle - Linear transducer.
- Torque - Torque-arm strain gauge.

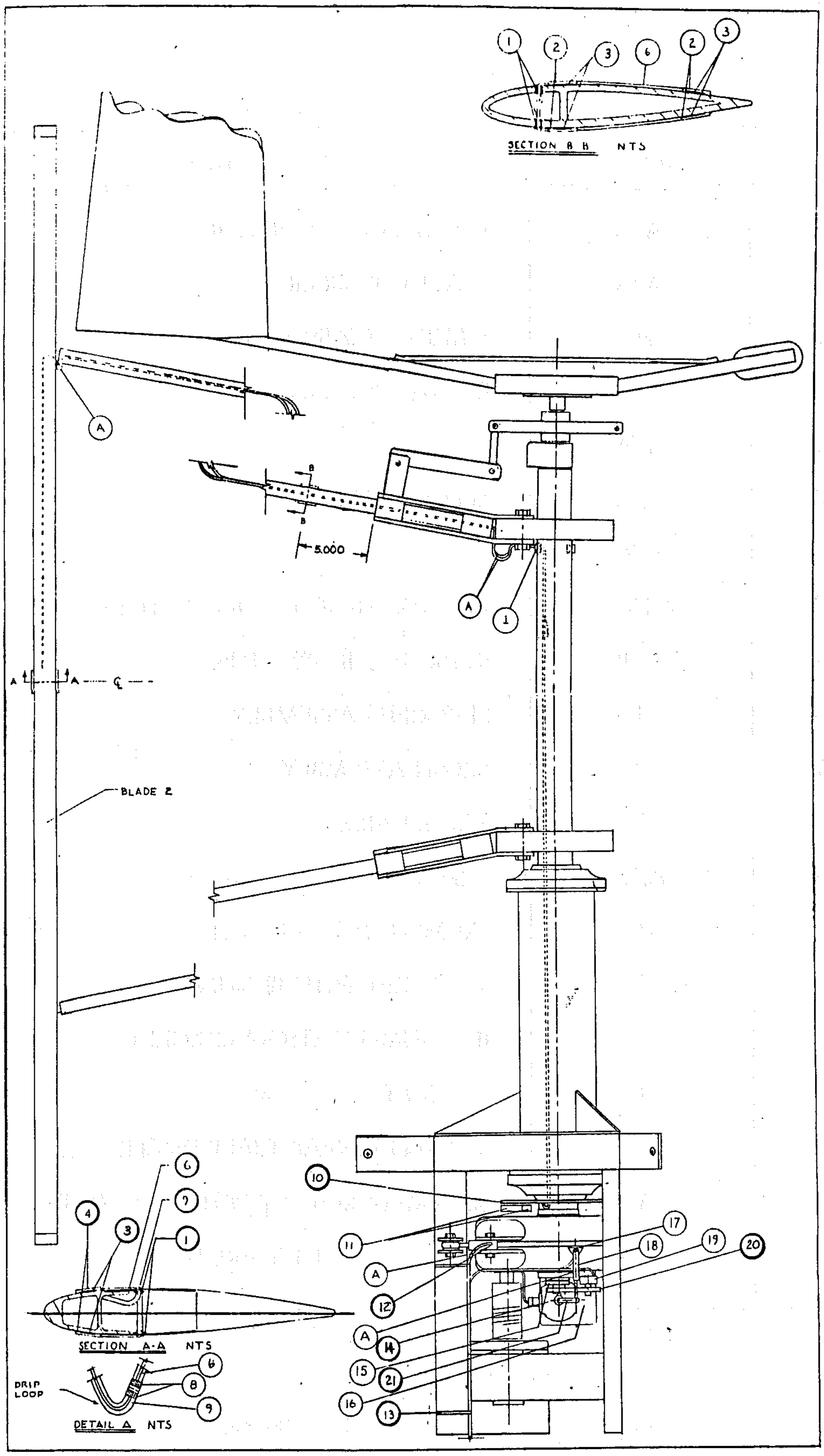
Short-Term Intensive Testing

Strain-gauge bridges were provided to measure:

- Bending stress at center of blade spar.
- Bending stress in flapping mode at strut root.
- Bending stress in lead-lag mode at strut root.
- Blade pitching force at L-link.

Only two of the above strain gauge measurements can be recorded simultaneously. The physical location of the instrumentation is shown in Figure 14.

The slip rings were mounted to the lower side of the disk brake plate above the gearbox. In this way, the disk would serve not only as a mount but also as a grease protector in the event grease dripped from the main bearing. The slip ring brushes were attached to two mounting brackets which were bolted to the upper side of the gearbox. The strain gauged torque arm was attached to the gearbox. The instrumentation bracket for the Trump-Ross torque transducer and the azimuth potentiometer was bolted to the bottom of the gearbox. The sprocket gear for the Trump-Ross was mounted on the lower end of the main shaft extending beneath the gearbox. The azimuth potentiometer sprocket was mounted on the actuator rod. A 6-ft wiring harness was fabricated to attach the individual instrumentation leads to a single connector. The harness includes connectors for the rotary potentiometer and torque arm, two brushes for the slip




a) Location.

Figure 14. Instrumentation.

| KEY | QUANTITY | DESCRIPTION |
|---|---|---|
| 1 | A/R | GROMMET 5/16-IN. ID |
| 2 | A/R | ELASTIC BARRIER |
| 3 | 20 | MM 350 STRAIN GAUGE |
| 4 | A/R | ELASTIC BARRIER |
| 5 | N/A | |
| 6 | A/R | BELDON 8434 CABLE |
| 7 | N/A | |
| 8 | 6 PR. | MS3106A-16S01P CONNECTORS |
| 9 | A/R | 0.188-IN. ID PVC TUBE |
| 10 | 1 | SLIP RING ASSEMBLY |
| 11 | 2 | BRUSH ASSEMBLY |
| 12 | 1 | STRAIN ARM |
| 13 | A/R | WIRE TIE |
| 14 | 1 | TRUMP-ROSS ENCODER |
| 15 | 1 | SPROCKET WITH BEARING |
| 16 | 1 | INSTRUMENTATION BRACKET |
| 17 | 1 | BRACKET |
| 18 | 1 | BOURNS LINEAR TRANSDUCER |
| 19 | 1 | BECKMAN ROTARY POTENTIOMETER |
| 20 | 1 | SPROCKET WITH BEARING |

b) Bill of Materials.

Figure 14. Instrumentation (Concluded).

rings and the linear transducer. An 80-ft wiring lead which connects to the 6-ft harness was also supplied.

Instrumentation was not supplied with the second and third prototypes; however, these units were provided with instrumentation brackets.

### 3.3.4 MANUALS

A manual was requested which described assembly, operation and maintenance of all equipment as well as manual installation on the tower. Erection of the tower was later added. The draft manual was modified several times to reflect modifications to the machine, davit, and instrumentation. Instructions for set-up, checkout and operation of the turbine were all revised as a result of differences in the trip mechanism supplied with the prototypes (see Section 3.1.5). The final manual (Reference 4) does not include modifications made by Rockwell subsequent to their receipt of the turbine nor does it include instructions provided separately by Pinson for the trip mechanism.

### 3.3.5 TESTS

It was recommended at the Phase I Final Design Review that Rockwell purchase a 42.5-ft Octahedron tower for installation at New Seabury, Massachusetts. Early in Phase II, Rockwell agreed to purchase the tower which was used to test the first prototype at New Seabury. This tower was to be shipped to Rocky Flats with the first machine; however, Pinson purchased a new tower and shipped it to Rocky Flats.

Vibration tests which were recommended at the Final Design Review were approved in Phase II. These tests were to be conducted on components of the first prototype in order to determine fundamental frequencies. These data would be used in analysis of data to be obtained from tower tests. These data were to be obtained by use of an accelerometer to acquire the frequencies of the blade and strut in both chordwise and edgewise bending. However, an accelerometer was not available from

Rockwell at this time and one was not located from local sources. ASI recommended that strain gauges be used in place of the accelerometer. While additional cost would be incurred, the gauges permit the flexibility to measure frequency in more than one direction at the same time. Also, tests on the assembled rotor would provide both blade and strut data simultaneously. During this time period, Rockwell had developed facilities for conducting standardized vibration tests on all their machines. Therefore, this task was transferred to Rocky Flats.

Spin tests of the turbine on a ground test stand were proposed to determine the effect of RPM and tilt-cam angle on the control forces transmitted to the actuator rod. These tests, which were approved by Rockwell, required the construction of the test stand and the acquisition of a spin motor and a motor controller. These tests are discussed in detail in Section 5.2.5.

# SECTION 4

# MANUFACTURING PROCESSES

Fabrication of the three SWECS prototypes was done using standard manufacturing processes common to metal fabrication shops, and electronic and electrical equipment fabrication. Each prototype was hand built. Fabrication problems encountered were typical of design development and generally were readily rectified. Delays in delivery, unavailability of parts in small quantity, and slow turn-around by local subcontractors were numerous and random.

Drawings of the completed first prototype were prepared. The trip mechanism was not included on the turbine drawings since it is a Pinson-supplied part and because it mounts on the tower rather than on the turbine. The list of drawings delivered to Rockwell is included as Appendix A. These drawings are available from Rockwell. Assembly of the SWECS is described in Reference 4. Description of the assembly of the trip mechanism was provided separately by Pinson.

## 4.1 TURBINE

### 4.1.1 GENERAL

The turbine consists of components and hardware designed specifically for the 1-kW high-reliability SWECS. Exceptions are the gearbox, bearings, strut stay rods, gearbox/alternator coupling, cowling and instrumentation which were all purchased components. The blade leading-edge extrusions, strut root castings, and blade tip caps were manufactured by subcontractors for the 1-kW turbine. Other services provided by subcontractors included:

- cutting and bending strut/hub connection plates
- flame cutting of hubs

- welding of mainshaft/hub components and bearing cartridge components
- centerless grinding of mainshaft
- galvanizing of bearing cartridge components
- heat treating of struts and blade leading edges
- anodizing of struts and blade leading edges
- painting of logo on V-vane

The remainder of the turbine components and assembly of the turbine was accomplished in-house using standard manufacturing processes.

The use of subcontractors incurred many delays in the fabrication process. Most of the delays are of the nature expected in a research and development effort wherein suppliers of services work at a job rate or on a minimum quantity basis. The result was a low priority effort by the subcontractor especially if it was a large-scale operation. This situation was often accompanied by an unrealistic estimate of time required to perform the service. The worst case was that of the strut root castings. In mid-January 1979, Pinson was told that the castings would be ready in 2-1/2 weeks. The castings were not delivered until the beginning of April 1979. Welding services were erratic in job completion and caused numerous delays. In one case, that of the initial davit (see Section 5.4), the welder compromised structural integrity of the finished product. Therefore, late in the fabrication of the first turbine prototype, in-house welding capabilities were provided by Pinson.

Difficulty was experienced with the blade leading-edge extrusions produced by a local supplier. Some of the extrusions, as received from the manufacturer, were found to be twisted as much as nine degrees. The American Aluminum Association specifies a standard tolerance in twist of less than three degrees over the eight-foot length. The extrusions which did not meet this specification were returned to the manufacturer for replacement. Meanwhile, a jig was built to rivet the blade afterbody skin to the leading-edge extrusion. However, because of the twist in the extrusion, undesirable buckles occurred between rivets. Local manufacturers, including Helio Precision Products, were consulted concerning this problem. The jig was then redesigned for use with extrusions with an acceptable amount of twist. The problem with the twisted extrusions introduced significant delay into the test program.

The purchase of parts in small quantities also resulted in delays as well as increased costs. In the case of specialty items such as the strut extrusions, leading-edge extrusions, and strut root castings, minimum orders were required. Also, off-the-shelf parts were often not available immediately in small quantities and long lead times were required for ordering. This occurred for the 25:1 gearboxes and rod ends. In one case, that of the aluminim sheet for the blade afterbodies, the stock size used in the fabrication was discontinued by all suppliers.

Problems were also encountered with shipping. The 15:1 gearbox initially selected was ordered in November 1978 for delivery by the next month. In February 1979, the supplier discovered that they had failed to fill the order properly. Delivery finally was made in March. Delays in receiving purchased components for instrumentation contributed to schedule delays.

Three shipping containers were fabricated of plywood and braced with 2 x 4s. The main shaft/weldment with the cowling attached was packed in one crate. The crate had to be modified at one end to accommodate the length of the unit. The blades and struts were packed in a second crate and the disassembled V-vane was packed in a third crate. When the machine arrived at Rocky Flats, it was observed that the end of the crate containing the main shaft/weldment had been ripped open. Also, the blades and struts were in disarray. Although significant damage was anticipated, none was revealed during inspection. The electrical system crates had arrived without damage. The tilt-cam assembly, instrumentation harness, electrical connectors and lightning rod were shipped by commercial delivery service. The trip mechanism was hand-delivered during a subsequent trip to Rockwell. The installation kit and spare parts were crated and shipped separately from the turbine.

The turbine is shown in Figure 15. Fabrication and assembly of the various components and subassemblies are discussed in the following sections.

### 4.1.2 BLADES

The three blades for each turbine are of a built-up construction using a sheet metal afterbody riveted to an extruded leading edge as shown in Figure 11. Since the leading-edge extrusion may have some permissible twist, the blade fabrication technique, primarily in the rivet pattern, allowed for the twist. A blade jig was designed for fabrication of the blades for the prototype machines. This jig made it possible to construct blades using extrusions with twist of less than three degrees.

The blades were fabricated as follows: strut connection tabs and pull rod lug were cut from aluminum and drilled to specifications. These pieces were welded to the leading-edge extrusions (see Figure 7). The extrusions were then heat treated from the T-4 temper to T-6, and the heat-treated pieces were anodized in a blue color. Aluminum sheet was break-formed to the afterbody shape and the C-spar was formed to shape. The leading-edge extrusion, afterbody, and C-spar were then clamped in the blade jib, rivet holes drilled and deburred, and the assembly riveted with flush rivets. The inboard side of the afterbody was cut to allow insertion and movement of the strut connection tangs (see Figure 7). Access holes were cut in the outboard side of the afterbody for assembly of the blades to the struts (see Figure 8). Covers were then cut and fit for the access holes, and then riveted and screwed in place (see Figure 9).

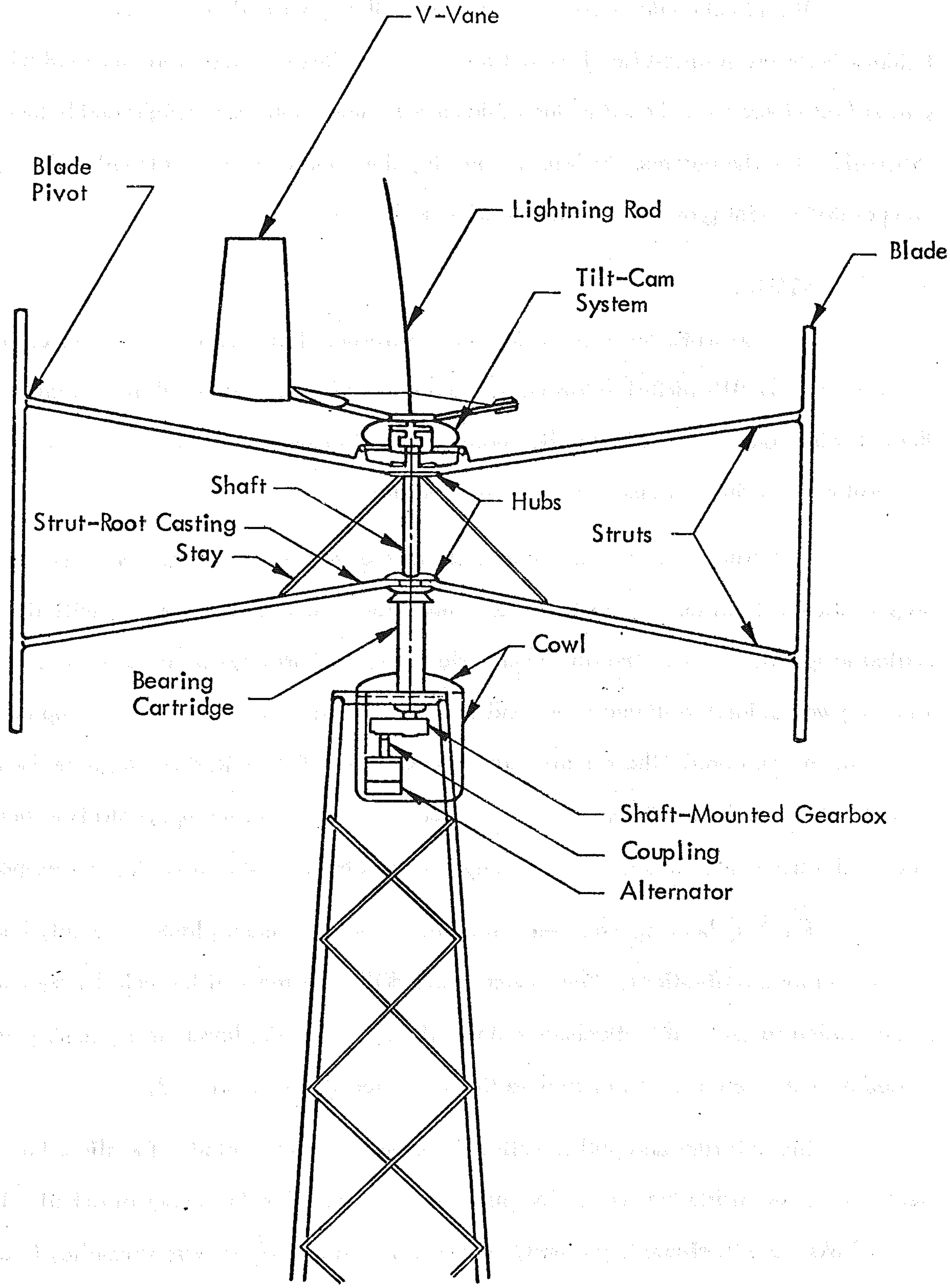



Figure 15. Turbine Components.

The leading edge was then drilled near the upper end of the blade and balance hardware inserted (see Figure 10). The fiberglass end caps were mounted with screws (see Figure 9). The set of three blades were made the same weight and balanced statically using the balance hardware. Finally, the afterbodies were etched, primed, and painted a light gray color with aircraft-quality paint.

### 4.1.3 STRUTS

The six struts for each turbine were constructed as shown in Figure 16 using a 6-inch NACA0015-airfoil extrusion purchased from Alcoa. As noted in Section 4.1.1, the extrusions and castings had to be purchased in minimum quantities, and delivery of the strut root castings was made several months late.

The struts were fabricated as follows: the strut root castings were cleaned and prepared for installation. Strut tangs for connection to the blade were cut, milled, and drilled to specifications. The aluminum airfoil-shaped extrusions were cut to length. The tang was welded to the outboard end and the castings were welded on the top and bottom of the root end. The castings are welded primarily to hold them in place during subsequent assembly (see Figure 17). Slots were then milled in the upper struts to accommodate the tilt-cam L-links. The assembly was then heat-treated from the T-4 temper to T-6.

The tang bearing was then installed. Root attachment plates were cut, bent, and drilled to specifications. The assembly was drilled at the root through the castings and extrusion to match the attachment plates (Figure 18). The lower strut assembly was drilled near the center to accommodate the mount for the strut stay rod.

The pull rods and pull rod slider bearings were fabricated. The slider bearings were then glued inside the strut. The pull rod was inserted and rod ends attached. Tilt-cam L-links were fabricated, painted, and installed in the upper strut assemblies (see Figure 19). Mounts for the stainless steel strut stays were fabricated and painted (see Figure 20). The root attachment plates were bolted in place.

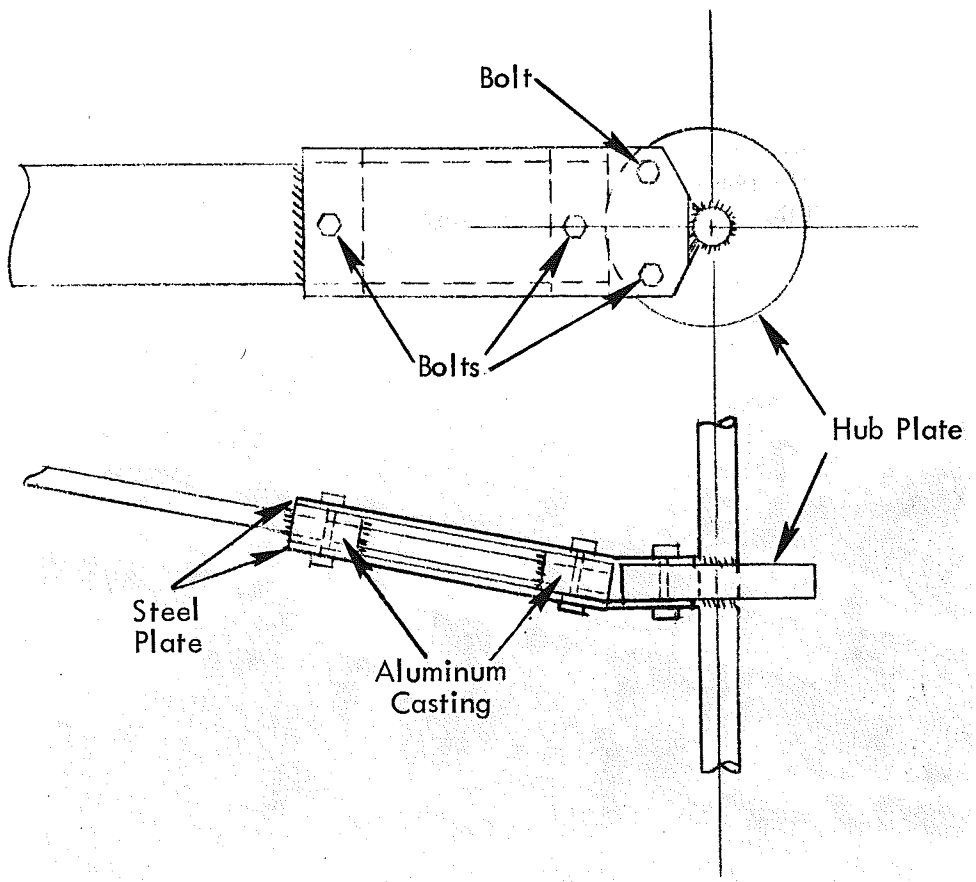



Figure 16. Strut Construction - Root Section.

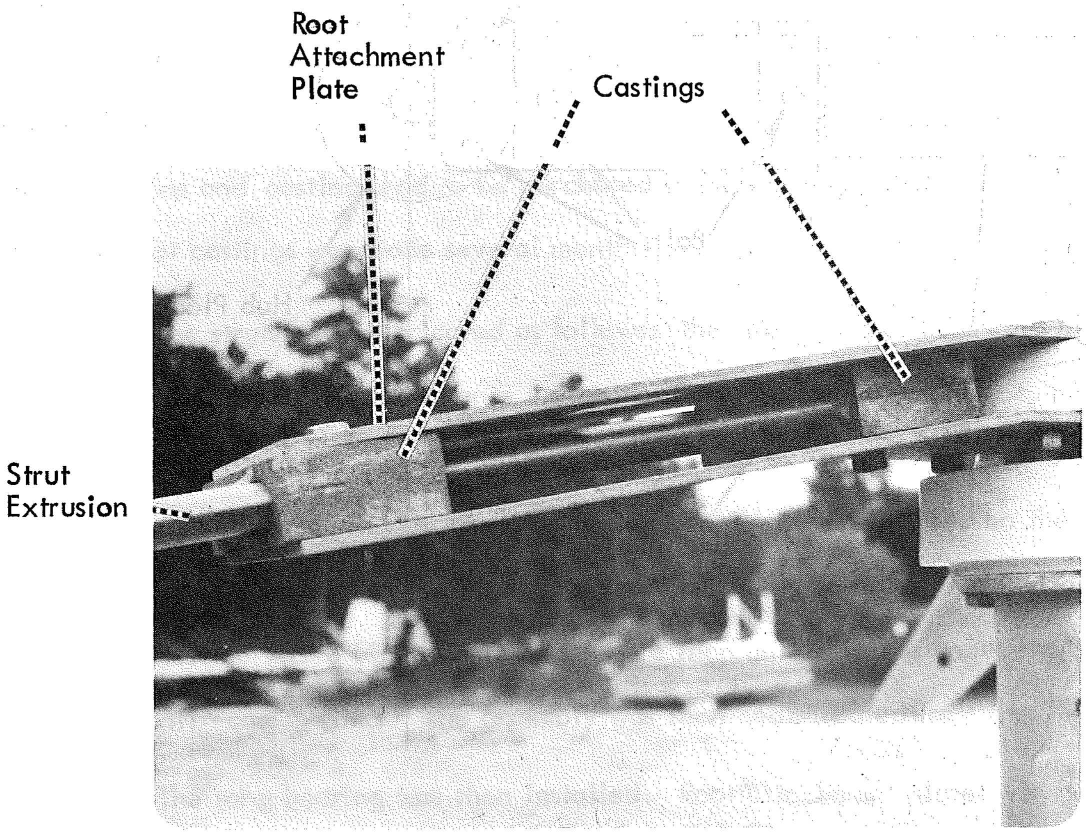



Figure 17. Strut Root Section Showing Airfoil with Castings Between Root Attachment Plates.

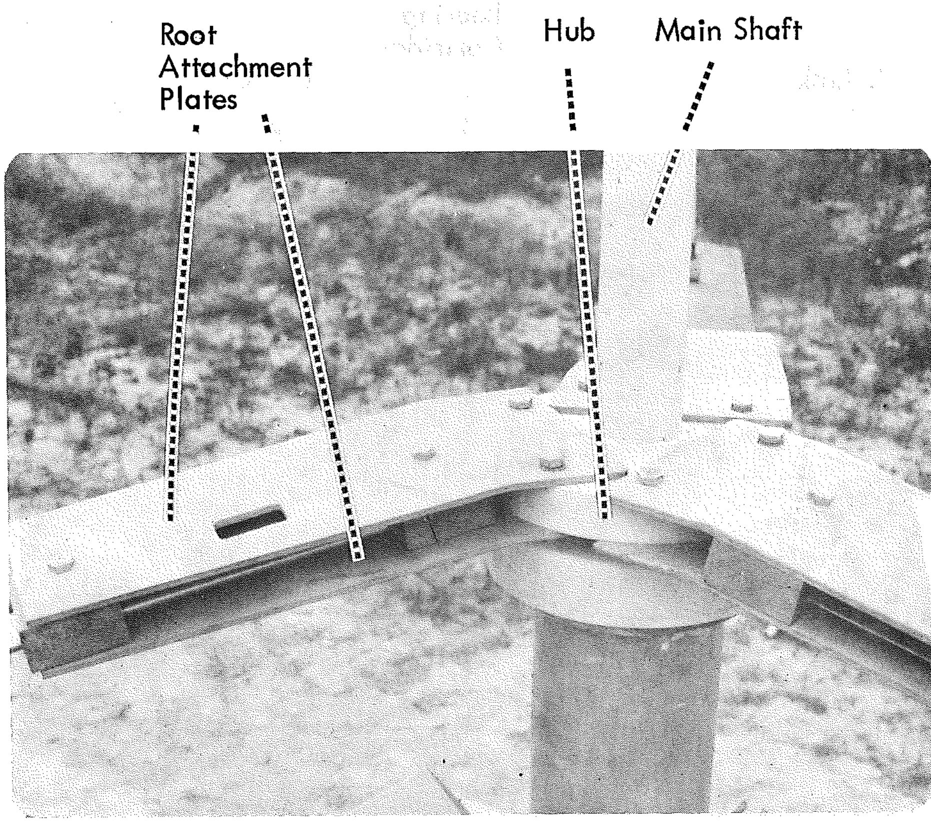



Figure 18. Lower Strut Root Section.

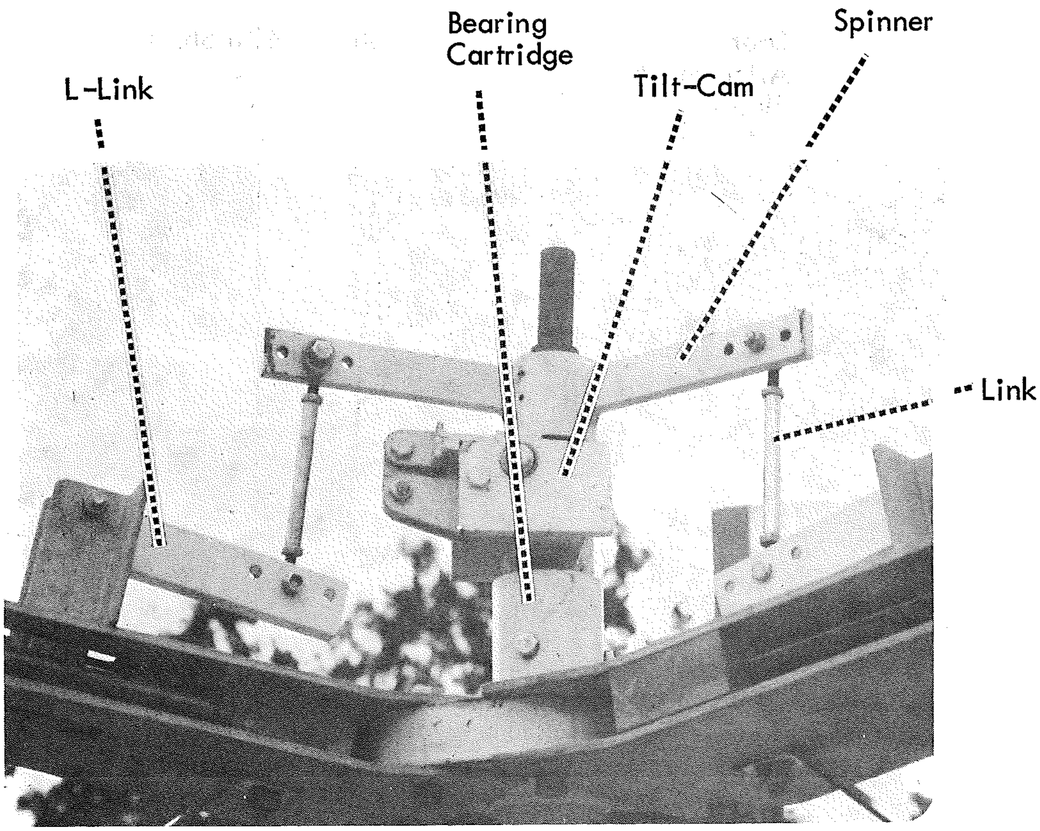



Figure 19. Tilt-Cam Assembly.

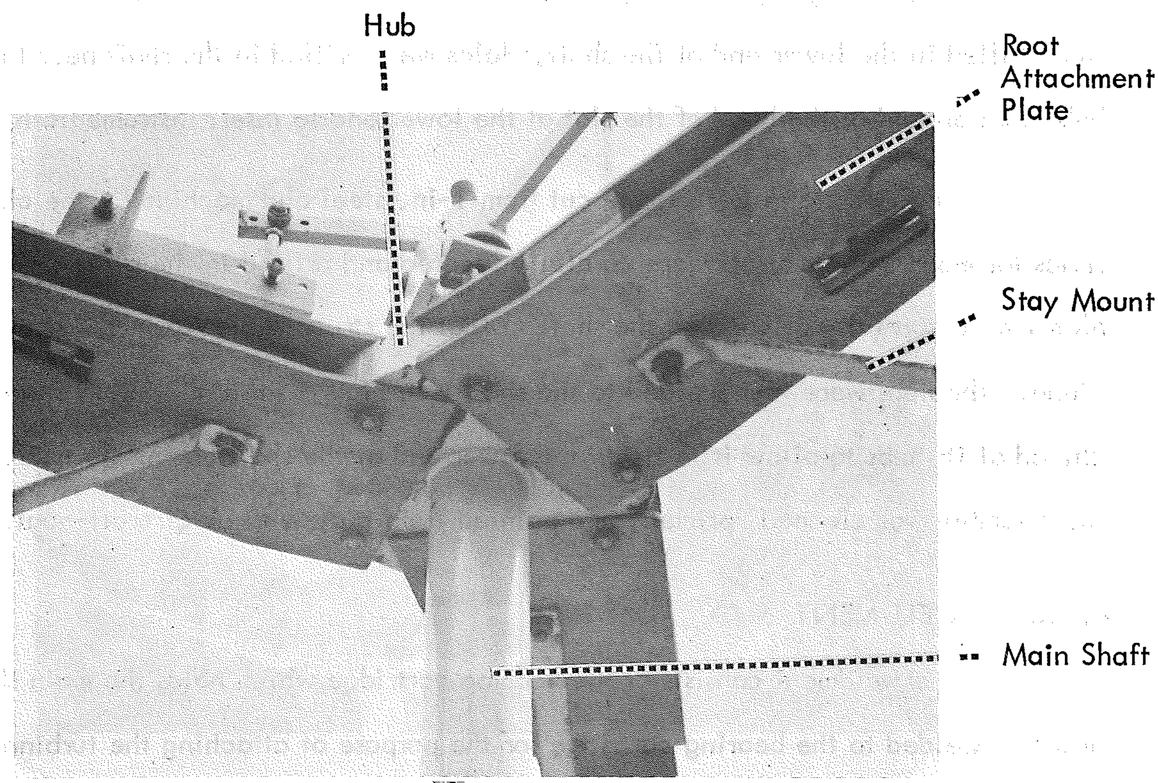



Figure 20. Upper Strut Root Section and Strut Stay Mount.

### 4.1.4 MAIN SHAFT

The main shaft and hub plates were fabricated as follows: the drawn-over-mandrel tube was centerless ground in the lower section where the main bearings ride. The bottom bushing was fabricated by cutting to length, turning on a lathe, and boring the access hole for the actuator rod. The bushing was welded onto the lower end of the shaft. The upper end of the shaft was turned to provide a recess for the tilt-cam bearing to be inserted. A keyway for the gearbox mount and a slot for instrumentation wires were milled in the lower end of the shaft. Holes were drilled in the shaft near the upper hub location and at the head of the slot at the lower end to insert instrumentation wires.

The hub plates were flame cut from 1-in. steel and machined to be circular. Holes for mounting the struts were carefully located and drilled in the plates. The hub plates were carefully aligned on the shaft so that the struts would lie in the same vertical plane. The hubs were then welded to the shaft (see Figures 18 and 20). A brake disk was machined at its hubs to allow it to fit on the lower end of the shaft above the gearbox. Finally, the assembly was cleaned, primed, and painted light gray with an aircraft-quality paint.

### 4.1.5 WELDMENT

The weldment consists of the bearing cartridge which holds the main shaft, structure welded to the bearing cartridge for the purpose of attaching the turbine to the top of an Octahedron tower, and the drive train/alternator support structure.

The weldment was fabricated as follows: steel plate was cut to shape for pieces of the tower-top adapter structure and holes were drilled for the tower bolts. End flanges were machined for the main bearings, a steel tube was cut to length for the bearing cartridge, and then the end flanges were welded to each end of the bearing cartridge. The tower-top adapter structure was welded together and to the bearing cartridge to form the basic weldment (see Figure 21).

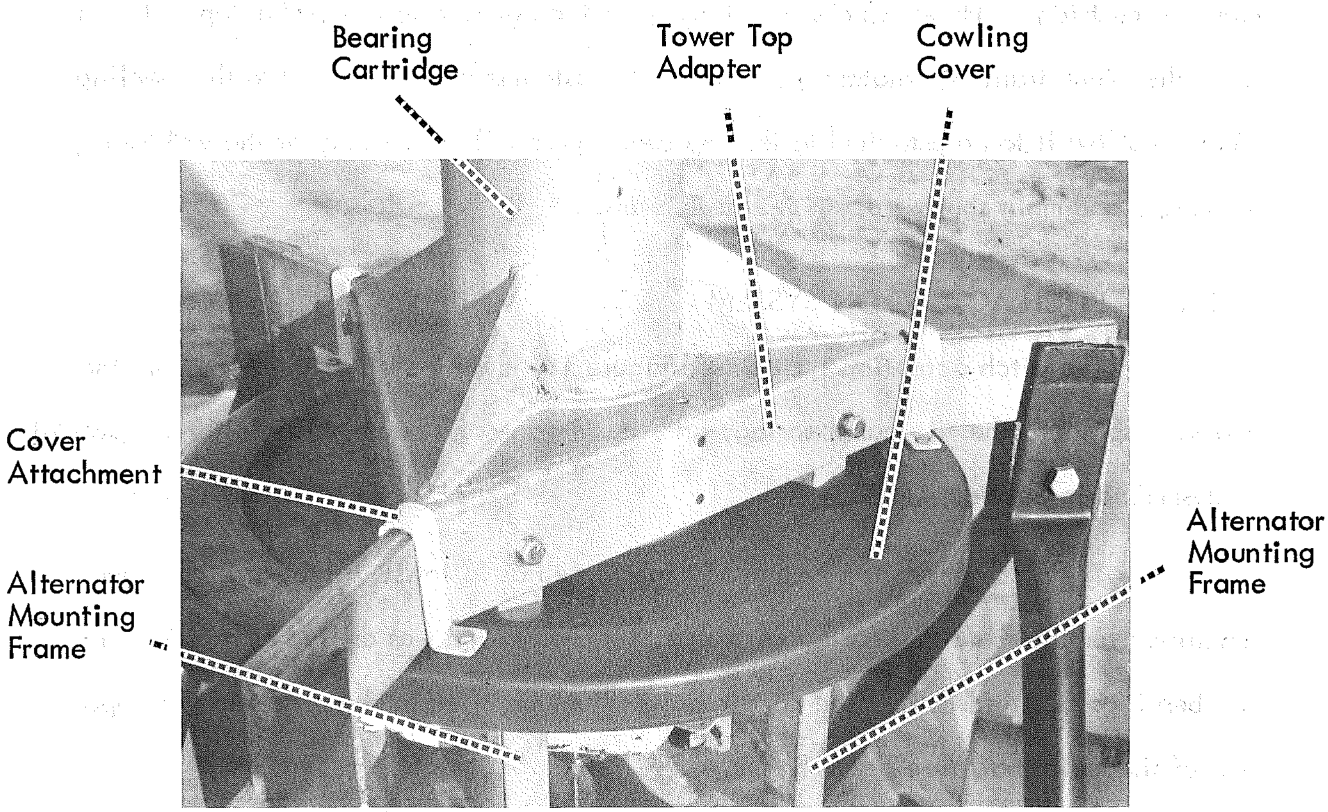



Figure 21. Weldment with Cowling Cover and Drive Train/ Alternator Frame in Place.

Plate was cut and bent to form the drive train/alternator support backbone. The backbone was welded and holes drilled for assembly bolts. Angle iron was cut and drilled for the remaining pieces of the support frame (see Figure 22).

The basic weldment and the drive train/alternator support frame pieces were cleaned and prepared, and then galvanized. The main bearings were installed in the bearing cartridge. Holes were cut in the top of the cowling to allow the top to be fit over the drive train/alternator support frame. Fasteners were attached to the cowling drum to allow it to be attached to the top (see Figure 21). Assembly of the weldment, cowling, and main shaft is described in Reference 4.

### 4.1.6 PITCH ACTUATION SYSTEM

The pitch actuation system (see Figure 19) is composed of the tilt-cam, the tilt-cam spinner, the tilt-cam bearing, and the V-vane and boom. The latter component is described in Section 4.1.7.

The pitch actuation system was fabricated as follows: a tube was cut and machined for the tilt-cam bearing cartridge. The cartridge was drilled as required and the bearings mounted in it. The cartridge was then mounted in the recess in the upper end of the main shaft (see Section 4.1.4).

Pieces for the tilt-cam spinner were cut from steel plate and tube. Holes were drilled in the spinner arms to mount the linkage to the pull rods. The spinner parts were welded together. The spinner was painted light gray.

Pieces for the tilt cam were cut, drilled, and welded. Holes for bushings were drilled. The pieces were painted light gray. Oil impregnated bronze bushings were inserted and the tilt cam was assembled. A cowling was shaped for the tilt cam from a plastic container.

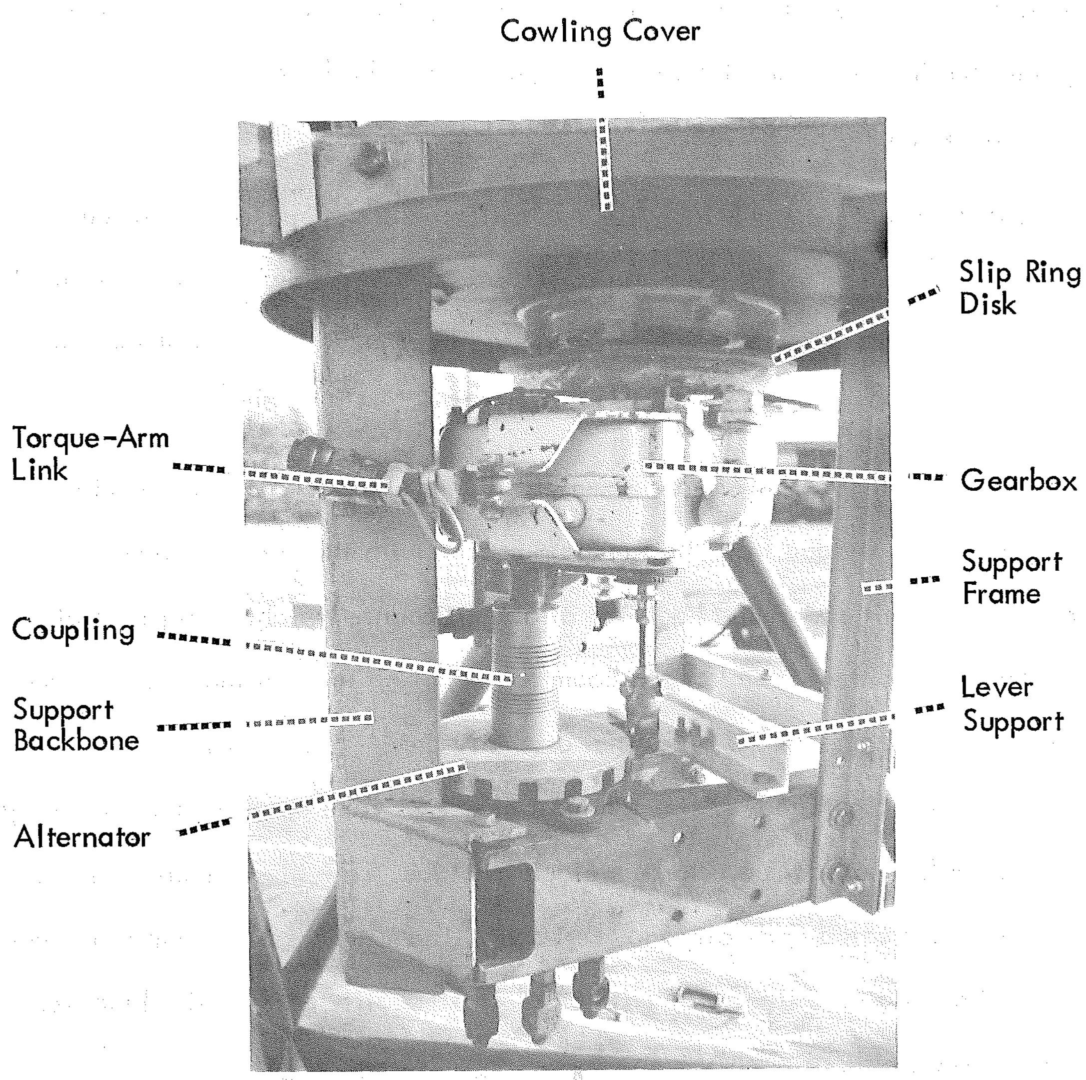



Figure 22. Drive Train/Alternator Frame.

### 4.1.7 AUTOMATIC SHUTDOWN/RESTART SYSTEM

The control system for automatic shutdown and restart works in conjunction with the tilt-cam system (see Section 4.1.6). The control system consists of the V-vane and boom (see Figure 13), the actuator rod and swivel, trip lever, trip lever mount, cable lanyard, and the Pinson trip mechanism (see Figure 23). The latter part is a factory-supplied item and is not described herein.

The control system was fabricated as follows. Aluminum sheet was cut and formed into a cambered airfoil shape. Holes were drilled and deburred, and the trailing edge riveted. End caps were fabricated and riveted internal to the ends of the vanes. A brace for the V-vanes was cut, bent and drilled.

Pieces for the boom were cut from aluminum rectangular tubes and aluminum sheet. The boom was welded from the tube and braced with the strap. Other strap was welded to the front end of the boom for attaching counterweights. A piece of angle was cut and welded to the aft end of the boom for mounting the V-vanes. Holes were drilled for the mounting bolts. During final assembly the V-vanes are fastened, positioned, and the bolts tightened. After the most effective vane angle is determined by testing by Rockwell, the vanes are to be welded in place. The attachment to the tilt-cam spinner was fabricated and bolted to the boom. The V-vanes and boom were then etched, primed and painted light gray with an aircraft-quality paint. The logo was painted on the lower side of each V-vane (see Figure 24).

The actuator rod was fabricated with a rod end at the upper end to connect to the tilt cam, and with internal threads at the lower end to accept a screw rod for adjustment. The screw rod was cut to length; however, the rod was lost in shipment and had to be replaced. The swivel at the lower end of the screw rod was fabricated (see Figure 25).

The lever which attaches to the swivel was cut from aluminum stock (see Figure 26). The attachment was made from a rod end. The lever was drilled at its fulcrum point. A

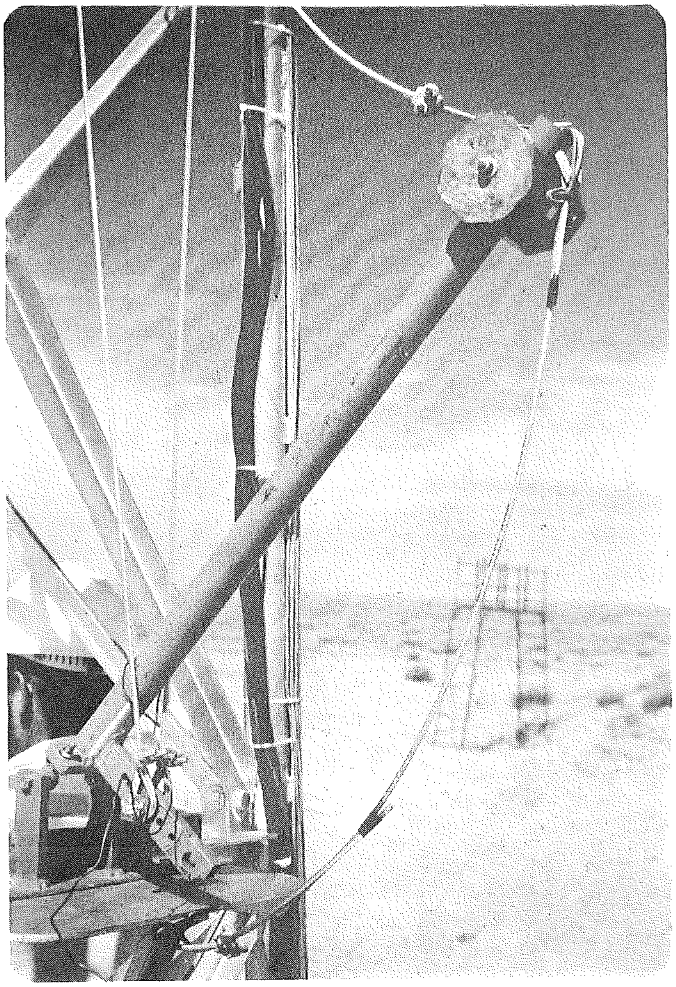


Figure 23. Pinson Trip Mechanism.


Figure 24. Logo on V-vane.

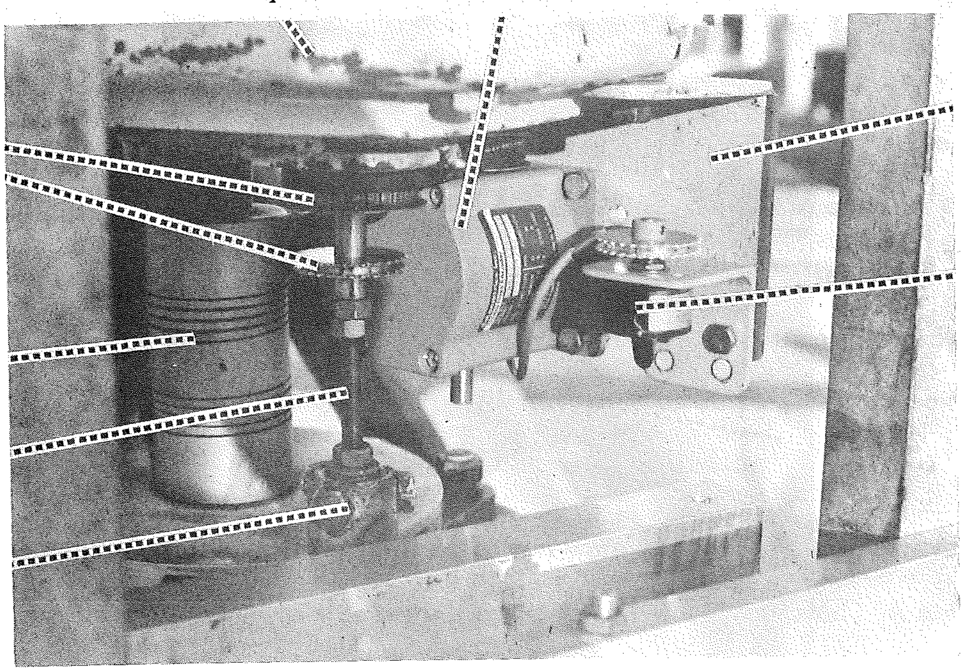



Figure 25. View Beneath Gearbox Showing Coupling, Actuator Rod Extension and Swivel, and Instrumentation.

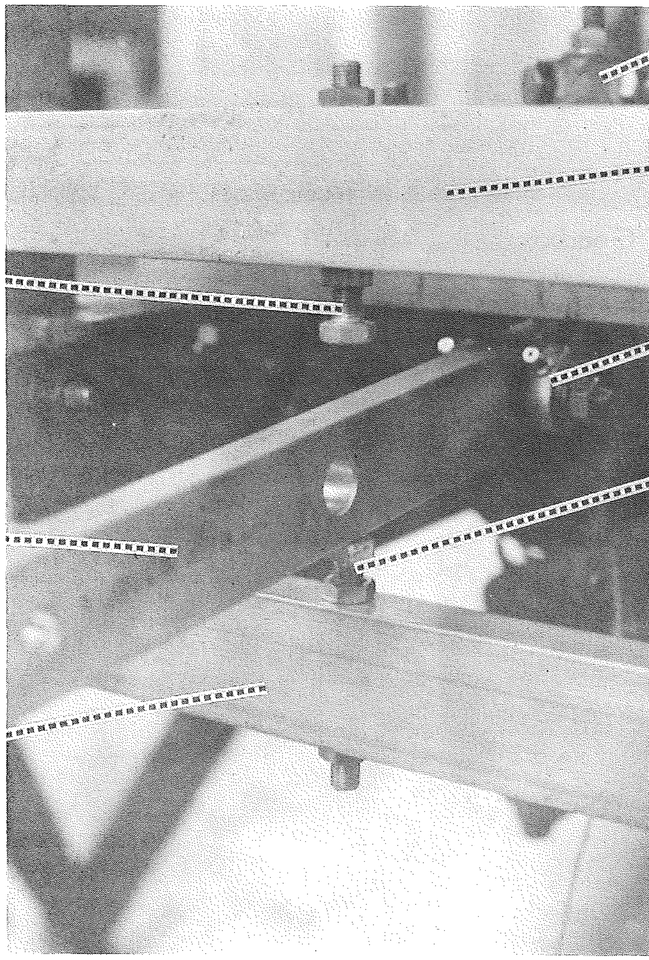



Figure 26. Trip Mechanism Lever Between Blade Pitch Angle Adjusters.

piece of channel was cut and drilled for attachment to the drive train/alternator frame. Rod ends were attached at the middle of the lower side from which the lever is pivoted. Two pieces of aluminum rectangular tube were cut and drilled to mount to the drive train/alternator frame. Holes were drilled in the middle of each to accept the stop screws used for adjusting travel of the lever (see Figure 26).

### 4.1.8 DRIVE TRAIN

The drive train consists of a 25:1 double-reduction gearbox mounted on the lower end of the main shaft as a speed increaser (see Figure 22), and a helical coupling which couples the gearbox to the alternator (see Figure 25). Both the gearbox and the coupling were off-the-shelf components. The gearboxes for the second and third prototype units were ordered for vertical running. A vertical running gearbox for the first prototype was not readily available; however, one for horizontal running was available and was ordered. The 25:1 gearbox was then modified for vertical running by removing the seals and grease fitting from a similar vertical-running 15:1 gearbox and mounting them in the 25:1 gearbox. This modification was covered by the factory warranty. The gearbox was painted light gray.

Special low temperature seals of Teflon were also purchased; however, these were not to be installed until initial testing by Rockwell was completed. A special grease manufactured by Dow Corning, known as "Molycoat", was used on the gearbox bearings. Being silicone based, it is capable of retaining lubricational values to -100$^{\circ}$F. General Electric Versilube F-50, a low-temperature silicone oil, was supplied with the turbine.

### 4.1.9 INSTRUMENTATION

The instrumentation included a linear potentiometer for tilt-cam position, a rotary potentiometer for tilt-cam vane wind direction, a Trump-Ross shaft encoder for RPM, and strain gauges for torque and structural stress measurements.

The strain gauges were installed as follows: on the blade spar at mid-span, at the strut root for measuring both in-plane and out-of-plane bending, on the L-link to measure pull rod stress, and on the torque-arm link to obtain torque readings. The continuity of all gauges was verified. The wires for the blade, strut, and L-link gauges were run to the main shaft and attached to connectors (see Figure 27).

A connector was attached to the torque-arm link wires (see Figure 22). Two wires were fished inside the shaft at the hole near the upper hub (see Section 4.1.4) and paper tubes inserted to hold the wires firmly against the shaft. Rubber grommets were inserted in the hole to prevent abrasion of the wires. Connectors specified by Rockwell were attached to the two main shaft wires at the upper end (see Figure 27). The wires were fished out of the main shaft through the hole drilled at the head of the slot near the lower end (see Section 4.1.4). These wires were to be soldered to the slip rings during final assembly (see Reference 4).

The slip rings were mounted above the gearbox on the lower side of the brake disk as shown in Figure 22 (see Section 4.1.4). Six holes were drilled and tapped in the disk plate for mounting the slip ring assembly. An additional set screw was added at the disk hub to prevent wobble and a sleeve was added to fill a small gap between the disk and the gearbox shaft.

A bracket was designed and fabricated to mount the Trump-Ross transducer and the azimuth-position transducer. The bracket was attached to the lower side of the gearbox (see Figure 25). Connectors for the transducers were attached. The sprocket for the RPM transducer was mounted on the lower end of the main shaft, and the sprocket for the azimuth-position potentiometer was mounted on the lower end of the actuator rod (see Figure 25). A mount was fabricated for the linear position transducer. This mount was later modified at Rocky Flats by Rockwell.

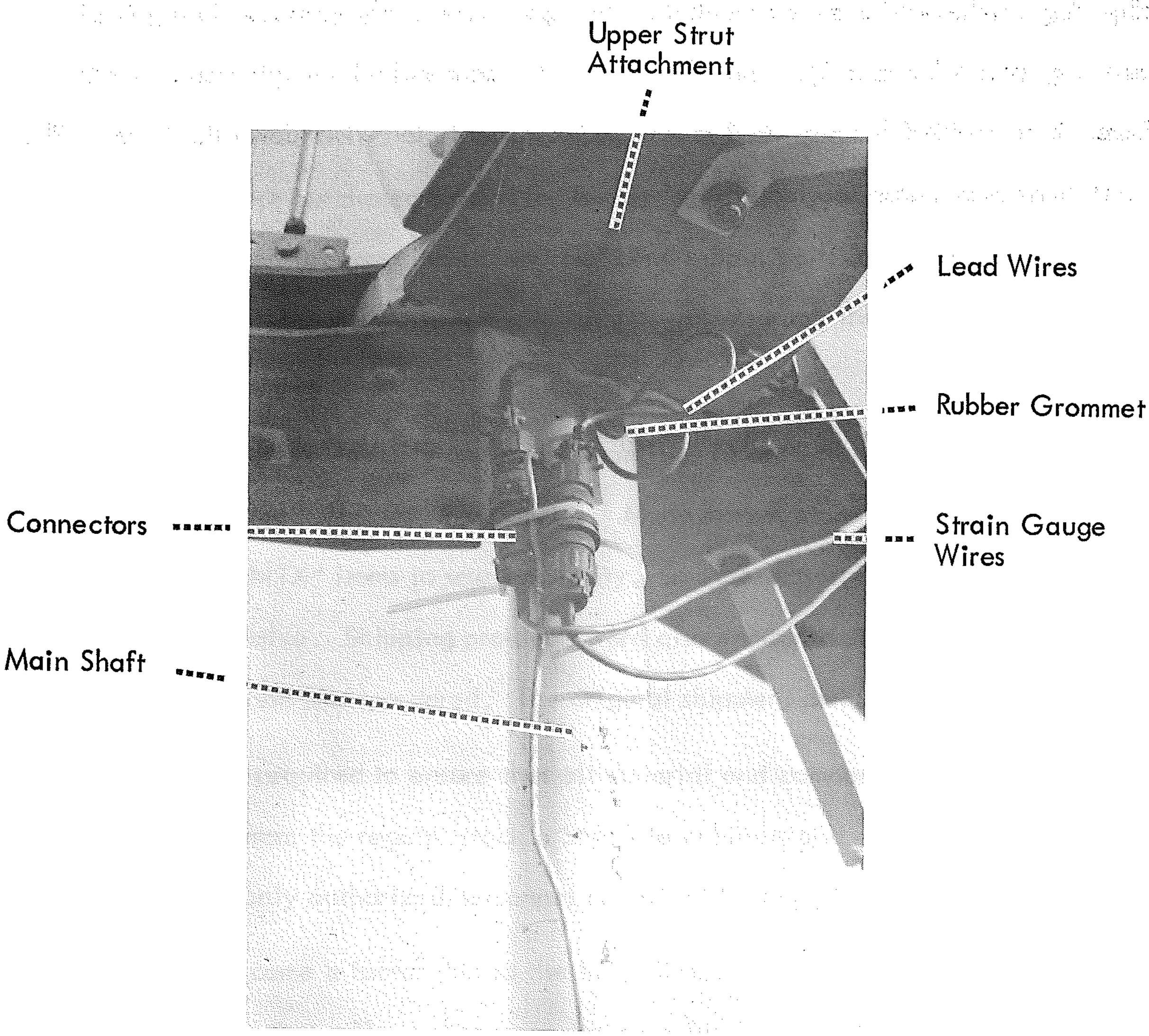



Figure 27. Strain-Gauge Connections at Upper Main Shaft.

A 6-ft harness was fabricated with leads and two connectors which could be used for the Trump-Ross transducer, azimuth-position potentiometer, or the torque-arm link. Another lead had the linear transducer attached. The final lead had the two slip-ring brushes which were mounted on the upper side of the gearbox during final assembly (see Reference 4). The other end of the harness had a single connector to fasten it to an 80-ft harness used to run the instrumentation wires down the tower. The 80-ft harness was also fabricated.

## 4.2 ELECTRICAL SYSTEM

### 4.2.1 GENERAL

The fabrication of the electrical system was accomplished using standard manufacturing processes. PC boards for the voltage regulator and dump load circuits were made in-house. Only painting of the enclosures was done by a subcontractor. Basic components were purchased except for the back panels. Induction coils for the alternator lightning protection circuit, and field and output coils for the alternator were hand wound. Some difficulty was encountered in wrapping the stiff wire on the output coil bobbins.

Due to the high quality and small quantities of parts required, it was often difficult for NPI to locate certain components. Many manufacturers would not supply "MIL-SPEC" or "JANTX" items in small quantity. In other cases, the minimum order was extremely expensive. Shipping problems were also encountered; one critical shipment appeared to be lost and was reordered. The original shipment arrived two months later.

Care was required to ensure that all material and components for this sytem were kept separate from the regular stock. Separate cabinets and drawers were designated for these items and only authorized personnel permitted to use them.

Space became a factor due to the large size of panels, cabinets and the even larger crates for shipping. The crates were designed for reuse and were built of heavy plywood and 2" x 2" stock, securely bolted together with carriage bolts.

The electrical system circuit diagram is shown in Figure 28. Each of the three systems supplied consisted of three metal enclosure cabinets containing electrical components, and one 24-Volt alternator. Fabrication and assembly of the various components and subassemblies are discussed in the following sections.

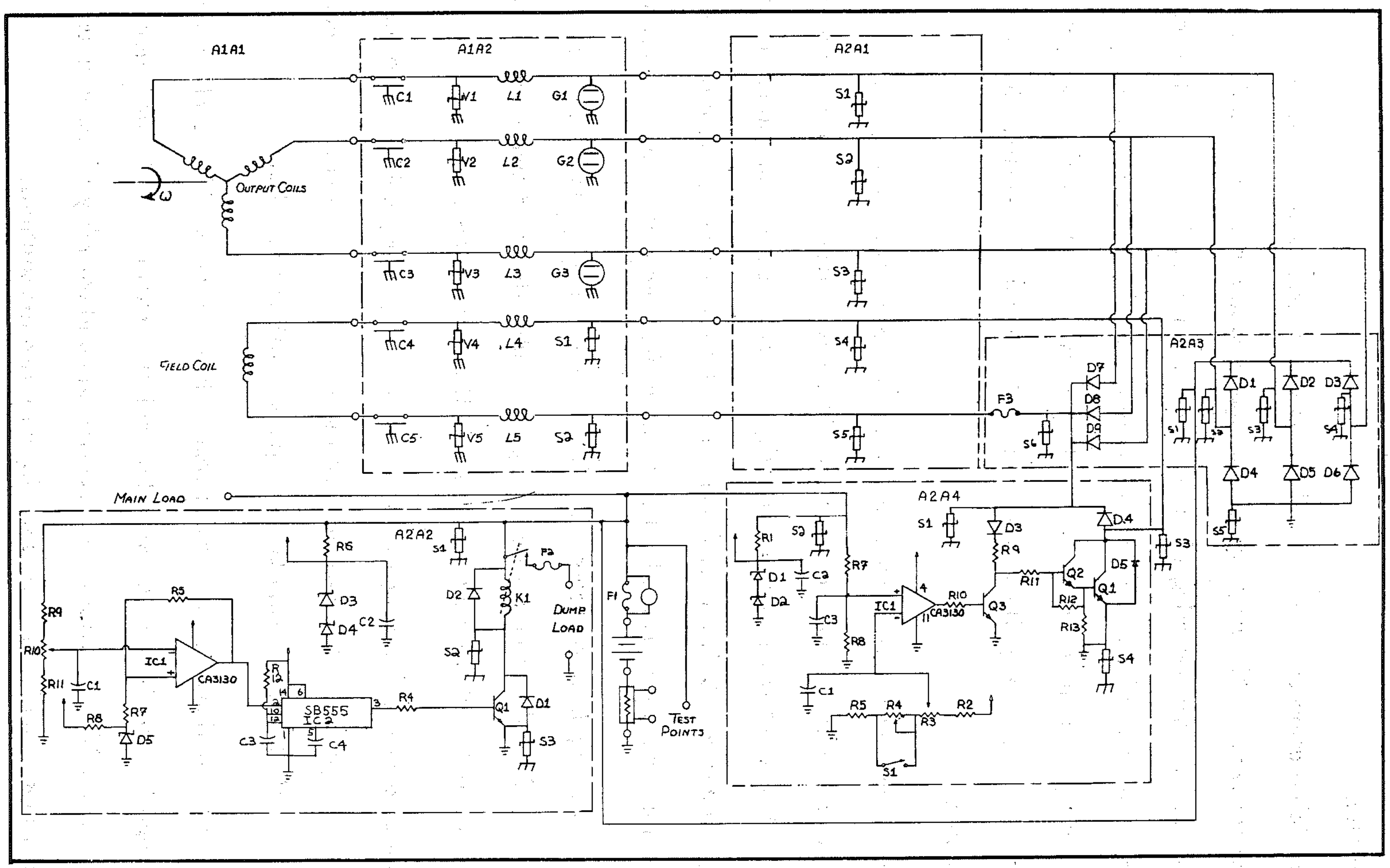



Figure 28. Electrical System Circuit Diagram.

### 4.2.2 ALTERNATOR - A1A1

The alternator (see Figure 22) was assembled as follows using the standard NPI main frame and coil support:

The field coil was custom wound on a waxed wooden mandrel mounted in a lathe chuck. Three pounds of #22 magnet wire were used. As the coil neared finished size, the supply spool was weighed frequently to ensure that the proper amount of wire, to the nearest ounce, had been used.

During the winding operation, baking varnish was applied with a paint brush to hold the coil together. Initially the wire was run through a pulley mounted in the bottom of a plastic pail containing the varnish, but this procedure was difficult to control. Subsequently, an electric heat gun was directed at the mandrel while the coil was being wound, heating the wire and brushed-on varnish thoroughly, allowing the varnish to flow evenly throughout the coil.

Upon completion of the winding, the mandrel-coil assembly was baked in an oven at 350°F for several hours to complete the drying of the varnish. After cooling, the mandrel was removed and the coil set aside to await further assembly.

The output coils consisted of three sets of four-coils in series and were wound with AWG #11 square magnet wire. Due to the small size of each coil, it was very difficult to wind the stiff wire around the nylon bobbins. Quite often the bobbins would crack and a new attempt was required. A small bench vise was used to help form the coils, as was a hammer and block of wood. The proper number of turns around each coil was critical in meeting the output specifications that were desired for this system. Nine turns were used for the prototype alternator.

When the output coils were completed, they were installed on the twelve-armed laminated steel coil frame, one coil of each set of four coils on every third arm.

After installing the fiberglass coil retainers, one end of each set of coils was connected together. Since magnet wire is coated with an insulating lacquer, care was taken to scrape all varnish off each wire before soldering. Heat shrink tubing was used to cover and insulate the connection. The wire between coils was carefully placed so as to be isolated from the coil frame.

The previously built field coil was now placed on the coil frame, and insulated from the frame and the output coils with "nomex" paper. The entire assembly was immersed in a bath of baking varnish for ten minutes, drained, then baked at 350°F for several hours to dry the varnish. After cooling and removal of excess varnish from the coil frame, it was assembled to the alternator main frame with four hex-head bolts. Tests were made to ensure that there were no short circuits between the coils and the main frame.

Final assembly included installing bearings, grease seals, locking C-rings and rotor. Since this alternator had no brushes, assembly and maintenance were greatly simplified.

To facilitate the connection of the output and field excitation cables, a special mounting ring was turned on a lathe using 1/2" Texolite. The disk was rough-cut with a sabre saw, then mounted on a scrap alternator main frame with the rear bearing shaft removed. A standard metal cutting tool was used to shape both the outer and inner surfaces. The disk was then drilled for connector mounting and labeled. The three output wires were cut, carefully cleaned of varnish and attached to ring connectors that were crimped and soldered in place.

To determine polarity of the field, the completed alternator was mounted on a dynamometer and connected to a control panel. If the field was connected properly, the unit started producing power; if not, field leads had to be reversed. Final field connections were made under the terminal mounting disk.

4.2.3 ALTERNATOR LIGHTNING PROTECTION - A1A2

This unit, shown in Figure 29, the middle-size of the three panels, contains components selected to minimize potential damage to the alternator due to lightning. Assembly problems unique to this unit included the fabrication of a mounting bracket for the feed-through capacitors (C1 - C5) and the three induction coils, L1 - L3.

The capacitor mounting bracket was made from a 1" x 2" piece of aluminum "L" stock, using hacksaw, 3/8" hand drill, Greenlee knockout punch and round metal file. Since the bracket itself served as an Earth Ground buss, it is connected to the Earth Ground terminal via a small aluminum buss bar mounted behind the back panel. Aluminum was used (instead of copper) to avoid the problems of dissimilar metals.

Induction coils L1 - L3 were fabricated locally after the original coils, similar to L4 and L5 on this panel, overheated. Each coil was tightly wound on a 2" dowel that was mounted in the chuck of a lathe and turned slowly. A spacer for each coil was made from the same material as the back panel. The #6 stranded copper cable was cut to length, tinned, and a ring connector crimped and soldered at either end.

All components were mounted on the previously prepared back panel using standard hand tools and appropriate hardware. It should be noted that it is difficult to acquire ring terminals that will adapt a small gauge wire to a 1/2" bolt. While such terminals are listed in several catalogs, their use is limited so as to require a special order.

Following a final electrical test, the panel was mounted in the prepared enclosure, the ground strap attached to the door and lower left mounting stud, and the entire unit crated for shipping.

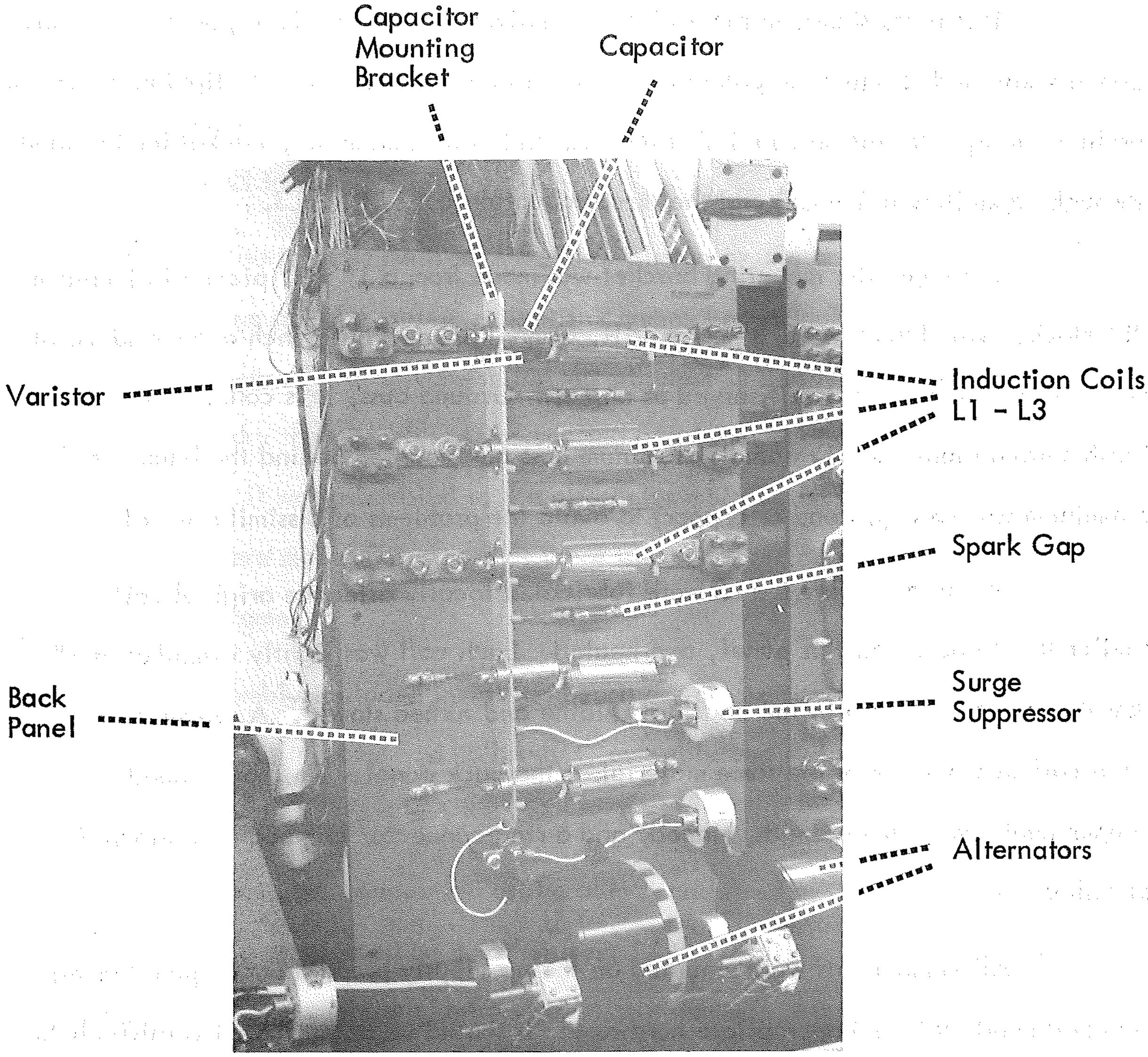



Figure 29. Alternator and Alternator Lightning Protection System.

### 4.2.4 MAIN CONTROL LIGHTNING PROTECTION - A2A1

The smallest of the three parts of the electrical control system, the A2A1, shown in Figure 30, consists of five surge suppressors, one on each of the conductors leading to the Main Control Panel.

The suppressors were installed on the previously prepared back panel using #6 hardware and appropriate hand tools. The white lead from each suppressor was run to the Earth Ground terminal and cut to length. Insulation was stripped from each lead, the wire tinned, and a ring terminal crimped and soldered on. All leads were attached to the 1/4" Earth Ground terminal and "fanned" for a neat appearance. Nylon cable clamps were used where necessary for proper "dressing" of the leads.

Because the conductors of the system are to "pass through" this unit, split bolts were selected to attach the black lead of each suppressor to its nearest conductor. Due to the large size of the three power conductors, the suppressor leads serving them were "doubled over" to provide a larger mass for a positive electrical connection. Each lead was cut to length and tinned.

A braided ground strap was prepared to run from the door panel to the lower left back panel/enclosure mounting stud, thence to the 1/4" Earth Ground terminal. The braided strap was heavily soldered at each connection point, then a hole was punched of proper size for attachment. Heat-shrink tubing was applied to the section between mounting stud and door panel to prevent short circuits and damage to the paint when the door was closed.

The completed panel was numbered and set aside for testing in the completed system. Once tested, it was installed in the enclosure after paint was removed from the lower left mounting stud. The ground strap was attached to the door and mounting stud. The required split bolts were packed in a small box and taped inside the enclosure after

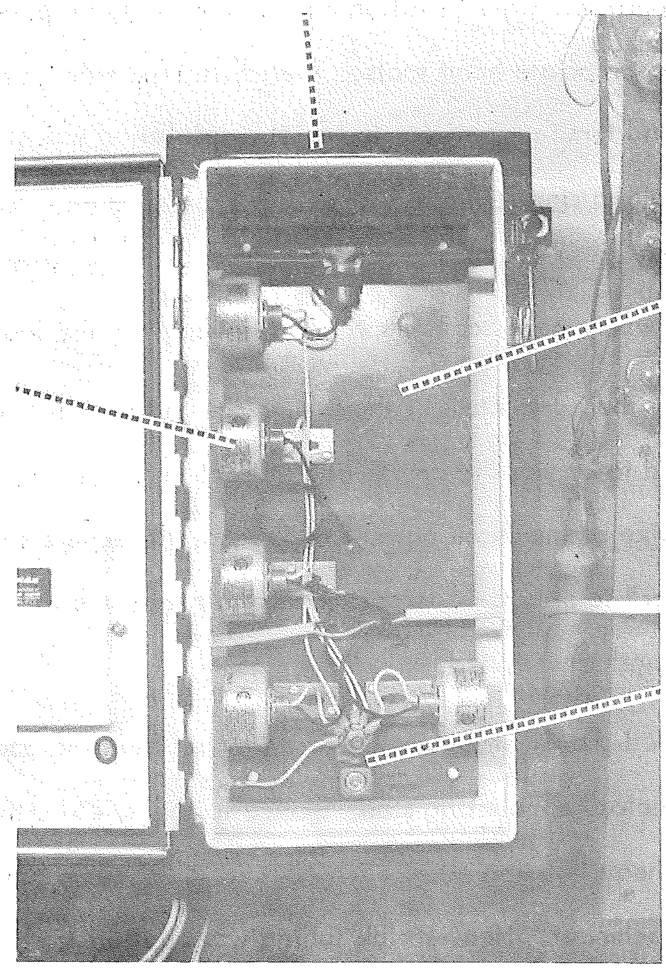



Figure 30. Main Control Panel Lightning
Protection System.

all dirt and metal fillings were removed. The unit was then bolted to its shipping container back-plane and the container finally bolted together.

### 4.2.5 MAIN CONTROL PANEL - A2

This unit, shown in Figure 31, which is the largest of the three panels, contains all the active electrical and electronic components. Each subassembly and all connectors were mounted using appropriate hardware and hand tools. Buss bars of solid copper were fabricated using hacksaw and drill press. Unit #1 had 1" x 3/8" buss-bars but this was excessive. Units 2 and 3, therefore, included 1" x 3/16" bars. A network of 12-gauge ground wire was installed at the rear of the panel to connect all surge suppressors to Earth Ground.

All components were wired in accordance with the schematic. High amperage lines were #6 gauge while all low current lines were 18 gauge or smaller. A small test-point panel was fabricated and mounted near the shunt. Four banana plug test points allowed easy measurement of system voltage and amperage.

The fuse block containing F1 and F2 was modified to accept rectifier-type fuses. Spare fuses were mounted nearby. Field fuse F3 was mounted on a locally fabricated bracket and a spare was located nearby.

All wires were coded to correspond with the Wire Run Key on the panel. All ring terminals were crimped and soldered. Cable ties were installed where needed to hold wiring firmly in place.

Threaded brass rods were cut and installed to connect input buss bars to each pair of diode rectifiers. A mercury relay was chosen to replace the more expensive armature relay originally proposed. It should be noted that the mercury relay had to be

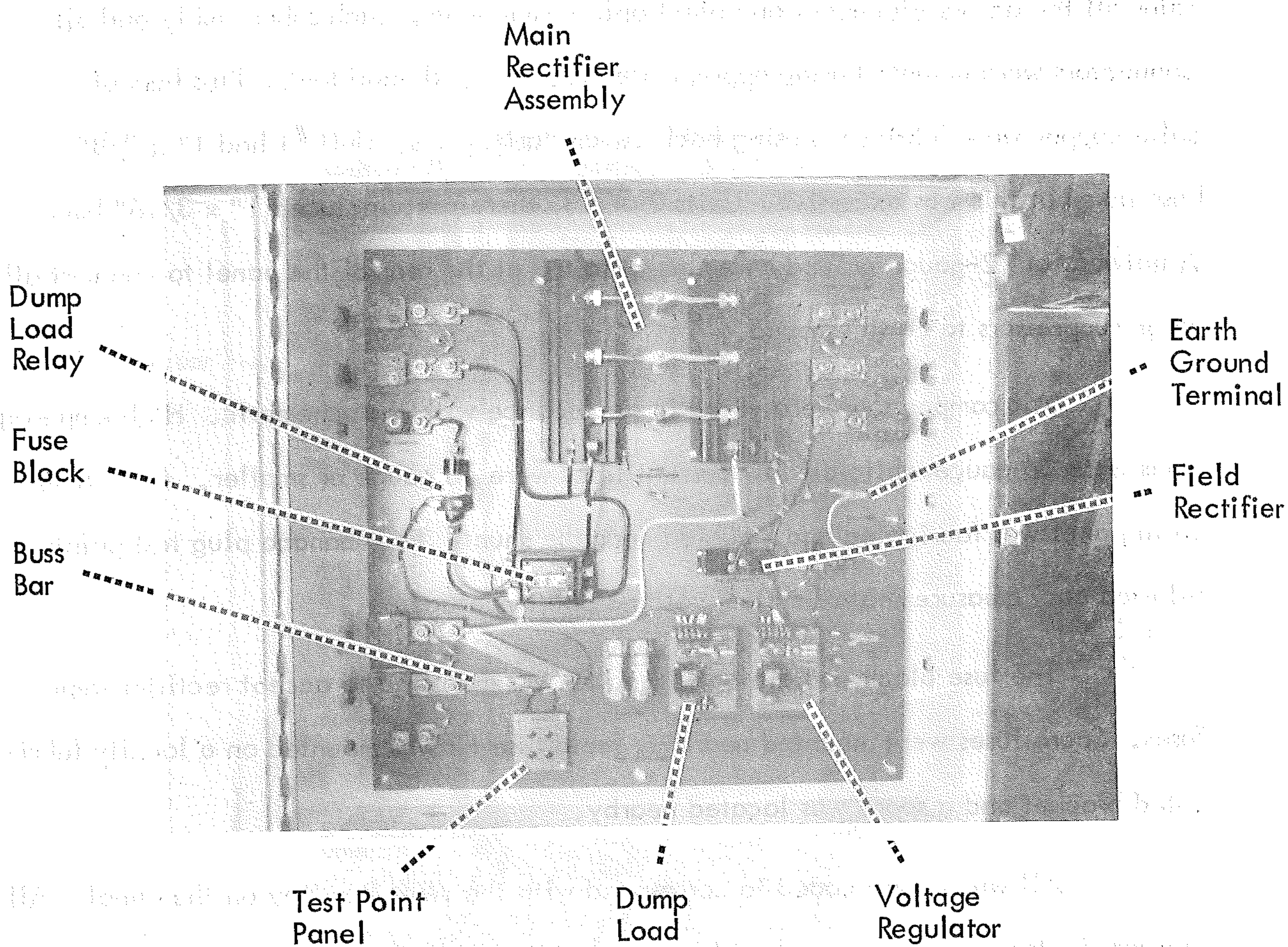



Figure 31. Main Control Panel.

oriented properly. The main panel had to be in the vertical position to ensure proper operation of the relay.

#### 4.2.5.1 RECTIFIER ASSEMBLY - A2A3

The main Rectifier Assembly serves to convert the three-phase alternating current (AC) power from the alternator to direct current (DC). Each large heat sink required milling at each diode location because the mounting stud was too short.

Each mounting hole was located and center punched. A 3/8" pilot hole was then drilled using a drill press. A 1" end mill was mounted in the chuck of a large lathe. The heat sink was then moved into the mill using the lathe's tool holder to provide horizontal pressure. A more satisfactory method might be to drill and tap each location so as to premit the diode's threaded mounting stud to screw into the heat sink.

Following the milling operation, the heat sink was reversed and lightly touched to the milling tool in order to remove the anodize to allow a positive electrical contact. Heat-conducting silicone grease was applied at each location and the diodes installed with standard wrenches.

The smaller Field Rectifier required drill press work and the removal of the anodize layer. Diodes were installed with the silicone grease and electrically connected as required.

All units were then put aside for final assembly on Panel A2 (see Section 4.2.5).

#### 4.2.5.2 VOLTAGE REGULATOR BOARD - A2A4

Following the design of the regulator and the drawing of a schematic, a printed circuit layout was done by NPI personnel. Several boards were produced. However, some components of MIL-SPEC quality have physical specifications different from more familiar industrial items. This discrepancy required that the board be redesigned and fabricated.

The heat sink for A1 required drilling to accommodate the transistor. This was accomplished using a standard drill press.

All components were soldered to the board in the conventional manner. Suppressors S1 - S4, however, were physically larger than the spec sheet had suggested, requiring that they be mounted vertically instead of horizontally.

After final testing and calibration, the board was sprayed with a compound designed to prevent moisture and fungus problems and set aside for final assembly.

#### 4.2.5.3 DUMP LOAD BOARD - A2A2

This circuit board was developed similarly to the A2A4 Voltage Regulator. Upon completion, it was decided to add a test point, requiring terminal strip and wiring to Pin 6 of IC1. This test point allows easier calibration of the Dump Load function.

### 4.2.6 ASSEMBLY ITEMS

#### 4.2.6.1 ENCLOSURES

All enclosures as received from the manufacturer were primed on the outside and painted with white enamel on the inside, except for the largest enclosure in System #1. That unit was unprimed due to its special order that included a gasket to prevent radio frequency interference (RFI). To reduce costs, the large enclosures for Systems 2 and 3 were stock items; the original neopreme gasket was removed and a special RFI gasket installed in its place.

All enclosures were drilled, then punched with a Greenlee hydraulic knock-out punch where necessary to accommodate the rain-tight conduit connectors.

After deburring, and drilling a 1/4" hole in the lower left corner of each door panel for the ground-strap connection, all units were taken to an automotive paint shop for finish painting. The large enclosure for System #1 required degreasing and priming, inside and out. It was then spray-painted white on the inside and dark blue on the outside, two coats each. The remaining enclosures were each given two coats of dark blue enamel. Standard commercial-grade air-dry automotive products were used on all enclosures.

Once painted, all enclosures had identifying labels silk-screened on the door panel, inside and out. All rain-tight conduit connectors and door-panel ground strap hardware were installed. Units were set aside to await final assembly.

4.2.6.2 BACK PANELS

All electrical and electronic components of each system were mounted on a rigid, non-conductive back-panel of Textolite. Each of the three back panels in the system was cut to size using a small sabre saw. All mounting holes were located and center punched. Pilot holes were drilled where necessary. Then the proper size hole was drilled using a drill press wherever possible, or a 3/8" hand drill. The throat depth of the drill press limited its use on the largest of the three panels. Each hole was deburred using a counter-sink or next larger size drill bit.

4.2.6.3 LABELING

At each component or connection location, a descriptive label was affixed to the back panels, corresponding to notations on the system schematic diagram. To protect the fragile rub-on symbols, they were applied to a sheet of clear acetate, then picked up with a piece of transparent tape and placed in the proper location. The tape, which covers the lettering, was then trimmed as necessary for a neat appearance.

For quantity production, silk-screening of all labels is recommended to ensure permanence and to save time.

# SECTION 5

# SUMMARY OF TESTING

## 5.1 GENERAL

Component testing initiated during Phase I continued into Phase II. This included tests of the horizontal wing of the control system and later of the V-vane which replaced it. Also, the tilt cam was tested on the test stand machine proposed during Phase I. The prototype alternator was preceded by a "breadboard" version which was bench tested. Tests of weld specimens were conducted to verify structural integrity and fatique characteristics.

System tests were conducted of the turbine mounted on a tower at New Seabury, Massachusetts. Both the breadboard and prototype electrical systems were connected to the turbine for field tests. The electrical systems had been previously bench tested with and without the alternator. The turbine also underwent spin tests to determine the effect of blade modifications on the control forces. In addition, tests were conducted with various versions of the davit using dummy loads.

A number of tests which were scheduled were not conducted. It was planned to connect the breadboard electrical system to the 25:1 gearbox, and turn the system with the Pinson motorcycle engine test rig. This test was to permit calibration of the system, determination of the gearbox efficiency, and a check on the electrical system output. The test was delayed because the torque transducer to be used for measuring output torque was being used on the test stand machine. In addition, the output information from the alternator, even if available, would serve no useful purpose for finalization of the electrical system design. Therefore, these bench tests were not conducted.

Vibration tests of turbine components including the blades, struts and main shaft as well as the assembled turbine had been scheduled, but were not carried out primarily due to lack of a suitable accelerometer. These tests were later performed at Rocky Flats (see Section 3.3.5). Calibration of strain-gauge instrumentation was planned; however, this task was also transferred to Rocky Flats to ensure consistency in the testing of all wind machines (see Section 3.3.3).

Subsequent to delivery of the first prototype to Rocky Flats, a series of tests were conducted by Rockwell. These included component vibration tests dynamometer tests, and controlled velocity tests (Reference 5).

## 5.2 TURBINE

### 5.2.1 TEST STAND MACHINE

The test stand machine was a Pinson Cycloturbine C2E modified to include some 1-kW high-reliability turbine components. The machine was used primarily to determine the performance and load characteristics of the tilt-cam control system under field conditions. The test machine, shown in Figure 32, consisted of the following major components:

- C2E blades modified to have pull rod connection ahead of hinge point and balanced to have the center of gravity at the quarter chord.
- Struts constructed of extruded aluminum NACA 0015 Section, each 7-ft in length.
- C2E main shaft.
- C2E hubs.
- C2E bearing cartridge.
- Tilt-cam pitch actuation control system.
- Mechanical shutdown device which required manual reset in order to restart the machine.
- Disk brake.

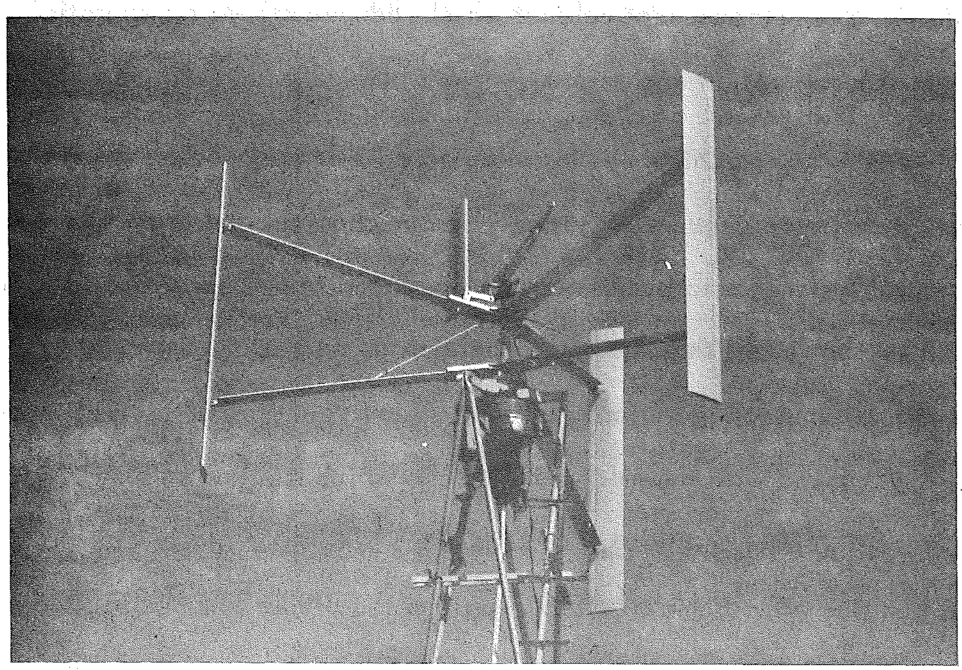


Figure 32. Test Stand Machine.

Except for the bearing cartridge and the hub/strut connections, the machine closely approximated the high-reliability turbine in size and configuration.

The Lebow #1104 torque transducer used in Phase I tests (see Reference 2) was refurbished and refitted to the main frame to measure shaft torque. This required machining a new set of stainless steel adapter sleeves. Shielded signal cable was routed directly to the main building. Conditioning and recording instrumentation was installed in a semi-permanent cabinet which reduced pre-test preparation time since only general calibration and zero adjustment needed to be set.

The test machine was installed on a 35-ft Octahedron tower at the New Seabury test site on January 10, 1979. The mechanical operation of the rotor and tilt-cam control system was checked out and was found to be operationally smooth. It was determined, however, that the pitch angle range on the blades was insufficient to provide positive controlling action. Later in January, during an 80 MPH windstorm, a problem was found with the mechanical brake which resulted in some damage to the blades resulting from an over-speed condition. The rotor blades and struts were removed from the main frame to effect repair to the blades and modifications to the struts to allow for higher blade pitch angles. It had been expected that damage to the blades would have been slight and that the blade could be repaired. However, damage was extensive and it was decided that it was more expedient to build a new set of blades.

The test machine was reinstalled at New Seabury in March of 1979. The machine incorporated a modified tilt-cam control system and new blades. The blades were fabricated basically the same as those planned for the prototype incorporating an extruded leading edge with a sheet metal afterbody. The machine did not include the wing for automatic overspeed control.

Run-in of the test machine was completed and the machine performed smoothly. Wear, as evidenced by unusual sounds, was not noted. Difficulty was encountered, however, in achieving self-starting. Inasmuch as the basic Cycloturbine C2E was a self-starting machine, the design of the tilt cam was carefully reviewed to determine if the cyclic pitch schedule induced by the system could be affecting the self-starting capability of the machine. This review revealed that the tilt cam as designed for the test machine provided the desired cyclic pitch schedule but did not provide sufficient motion of the pull rods to achieve blade pitch angles necessary to achieve self-start of the machine. The detailed review of the design also revealed that the kinematics of the tilt-cam mechanism were inducing an undesirably high collective pitch in the blades which was largely responsible for the inability to self-start.

The test machine proved to be effective in the prototype development. As intended, it provided valuable data on the tilt-cam system operation which resulted in modification of the initial design. Without the test machine, these data would not have been provided until the first prototype was in operation. In addition, the unscheduled refurbishment of the test machine brought to light problems inherent in the leading-edge extrusions and in the fabrication of the blades when some twist was present in the extrusions (see Section 3.1.1).

### 5.2.2 PROTOTYPE

The first prototype of the 1-kW high-reliability SWECS was tested on a 42.5-ft Octahedron tower supplied by Rockwell. The tower was located next to the main control shed at the New Seabury test site. This location was convenient in that the electrical cable and instrumentation wires were readily led into the control shed.

Instrumentation used for the prototype tests included a wind speed sensor, an RPM sensor (using magnetic pickups), a strain-gauged beam to measure control force, and a compilator from NPI to measure electrical output. Blade pitch was determined by calibration of the mechanical linkage used to change the cyclic pitch angle. The wind speed transducer was a Maximum 3-cup anemometer mounted on a boom from the Octahedron tower. The RPM transducer consisted of two magnets mounted on the high speed shaft which were used to induce a voltage in a nearby coil which in turn generated a signal whose frequency was proportional to RPM.

The NPI instrumentation was calibrated and prepared for testing the performance of the wind turbine. This instrumentation consisted of a three-channel compilator and input signal conditioning box. Data were collected and sorted into 32 bins each for the turbine electrical power output and RPM sequentially at one-second intervals along with wind speed information. The signal conditioning box accepted analog voltage proportional to the voltage and current of the alternator load. It multiplied these and scaled them so that each storage bin in the compilator had a width of 47 watts. It also conditioned and scaled the output of the RPM transducer so that each storage bin in the compilator had a width of 4.8 RPM. A bin width of 1 MPH was used for the anemometer input. The system collected data to generate frequency distribution of wind speed, electrical power and RPM. These distributions were used to generate the power versus wind speed, and tip speed versus wind speed curves that characterized the performance of the turbine for a given load condition.

#### 5.2.2.1 FIRST SERIES

The first prototype, shown in Figure 33, was installed at the New Seabury test site on June 1, 1979. The machine was installed uninstrumented. This was due primarily to the unavailability of the special slip rings to be provided by Rockwell. Strain gauges

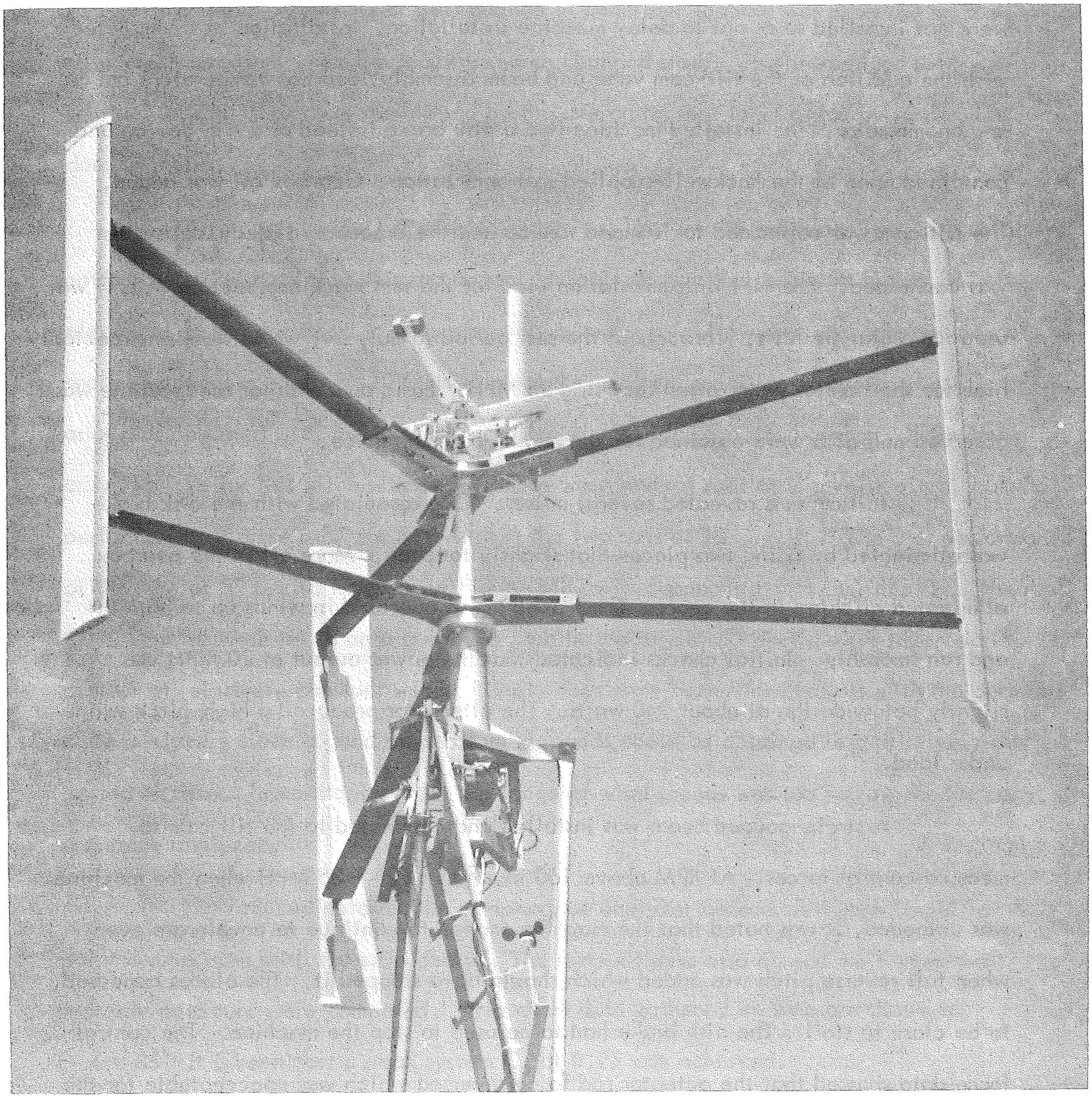


Figure 33. First Prototype - Series I Tests.

were not installed so as not to delay machine installation. Installation was completed with the addition of the tilt-cam vane and boom assembly, gearbox temperature gauge, and anemometry. The installed machine had a disk brake instead of a trip device and contained none of the Rockwell-supplied instrumentation. Gearbox oil was added. The tilt cam was calibrated to $10^{\circ}$ and tuned, and the breadboard electrical system was connected. The NPI instrumentation used for the test machine (Section 5.2.1) was used for prototype tests. Throughout the test period to July 24, winds were unexpectedly high for the time of year, often reaching 25 MPH. Basic operation of the machine was observed and data were obtained for the machine performance.

Initial tests revealed several noises. One associated with the disk brake was eliminated by filing two pieces that slightly touched. More oil in the gearbox eliminated clicking in the gears. The machine was operated in winds up to 30 MPH and ran smoothly. Initial checks indicated that the power output at 20 MPH was slightly below design at about 940 watts. The alternator produced a high-pitch whine under load.

A strain-gauged beam was installed and connected to the tilt cam to measure control forces. At RPM above 160 in winds of 25 - 35 MPH when the machine was unloaded, it was noted that the machine tended to continue to accelerate even when full reverse pitch was added which should have stopped it. The blades appeared to be close to stall. The disk brake had to be used to stop the machine. The control force data showed that the actuator rod force reversed which was unacceptable for the trip mechanism operation. This problem necessitated redesign of the blades (see Section 3.1.1).

An NPI dynamic loading switch was used to serve the function of a dump load circuit. The tests were run with the dynamic loading switch connected to the battery and a 0.66 ohm resistive load. This effectively limited load voltage excursions to 2 volts or less. A 100 - 200 watt change in generator loading was observed on the strip chart recorders when the loading switch changed state. This introduced some scatter, but the effect was diminished by the averaging that takes place by sorting the data into bins.

A run was conducted with no electrical load on the turbine. The wind velocity, power, and RPM data from this run appear in Table 8a and the results in Figure 34. The electrical system appeared to be performing as expected. However, the turbine did not produce adequate power at 20 MPH to meet the contract specifications. The best performance was obtained with the turbine operating at $10^{o}$ cyclic pitch; however, there were only two runs for this pitch schedule. There were several runs at $5^{o}$ cyclic pitch, but the performance of these runs was poorer than the two runs at $10^{o}$ cyclic. The best performance of the runs at $5^{o}$ cyclic is shown in Figure 34b, with supporting data in Table 8b. The runs at $10^{o}$ cyclic were taken on a gusty day, while the runs at $5^{o}$ cyclic were taken during periods of relatively constant winds. Gusty days were better for analysis with the performance analyzer, since a good range of wind speeds could be obtained in a relatively short period of time. In constant winds, the range of wind speeds was too narrow for the performance analyzer.

The reduced data for the performance analyzer agreed well with single point comparisons with the strip charts. The reduced data also agreed well when two separate data runs were compared. Strip chart data gathered in June are shown in Figure 35. It is seen that a peak system $C_p$ of 0.25 was achieved.

The temperature of the output coils of the alternator was monitored for some of the initial runs. It was running at about 12-15$^{o}$C above ambient which was within expectations. It was difficult to make a judgment from this information due to the long thermal time constants involved and the problems associated with using

| Bin # | WIND SPEED (V) COUNTS PER BIN | % * > V | AVG. BIN SPEED | POWER (P) COUNTS PER BIN | % * > P | AVG. BIN POWER | RPM (N) COUNTS PER BIN | % * > N | AVG. BIN RPM |
|---|---|---|---|---|---|---|---|---|---|
| 0 | | | | | | | | | 4 |
| 1 | | | | | | | | | 9 |
| 2 | | | | | | | | | 14 |
| 3 | | | | | | | | | 20 |
| 4 | | | | | | | | | 26 |
| 5 | | | | | | | | | 32 |
| 6 | | | | | | | | | 38 |
| 7 | | | | | | | | | 43 |
| 8 | | | | | | | | | 49 |
| 9 | | | | | | | | | 55 |
| 10 | | | | | | | | | 61 |
| 11 | | | | | | | | | 67 |
| 12 | | | | | | | | | 72 |
| 13 | | | | | | | | | 78 |
| 14 | | | | | | | | | 84 |
| 15 | 4 | 97 | 15 1/2 | | | | | | 90 |
| 16 | 9 | 89 | 16 1/2 | | | | | | 96 |
| 17 | 29 | 65 | 17 1/2 | | | | | | 101 |
| 18 | 33 | 38 | 18 1/2 | | | | | | 107 |
| 19 | 32 | 12 | 19 1/2 | | | | 3 | 98 | 113 |
| 20 | 8 | 5 | 20 1/2 | | | | 18 | 87 | 119 |
| 21 | 3 | 2 | 21 1/2 | | | | 24 | 73 | 124 |
| 22 | 3 | | 22 1/2 | | | | 47 | 45 | 130 |
| 23 | | | | | | | 50 | 14 | 136 |
| 24 | | | | | | | 20 | 2 | 142 |
| 25 | | | | | | | 4 | | 148 |
| 26 | | | | | | | | | 153 |
| 27 | | | | | | | | | 159 |
| 28 | | | | | | | | | 165 |
| 29 | | | | | | | | | 170 |
| 30 | | | | | | | | | 177 |
| 31 | | | | | | | | | 182 |

* Percent of counts which exceeded a given bin range.

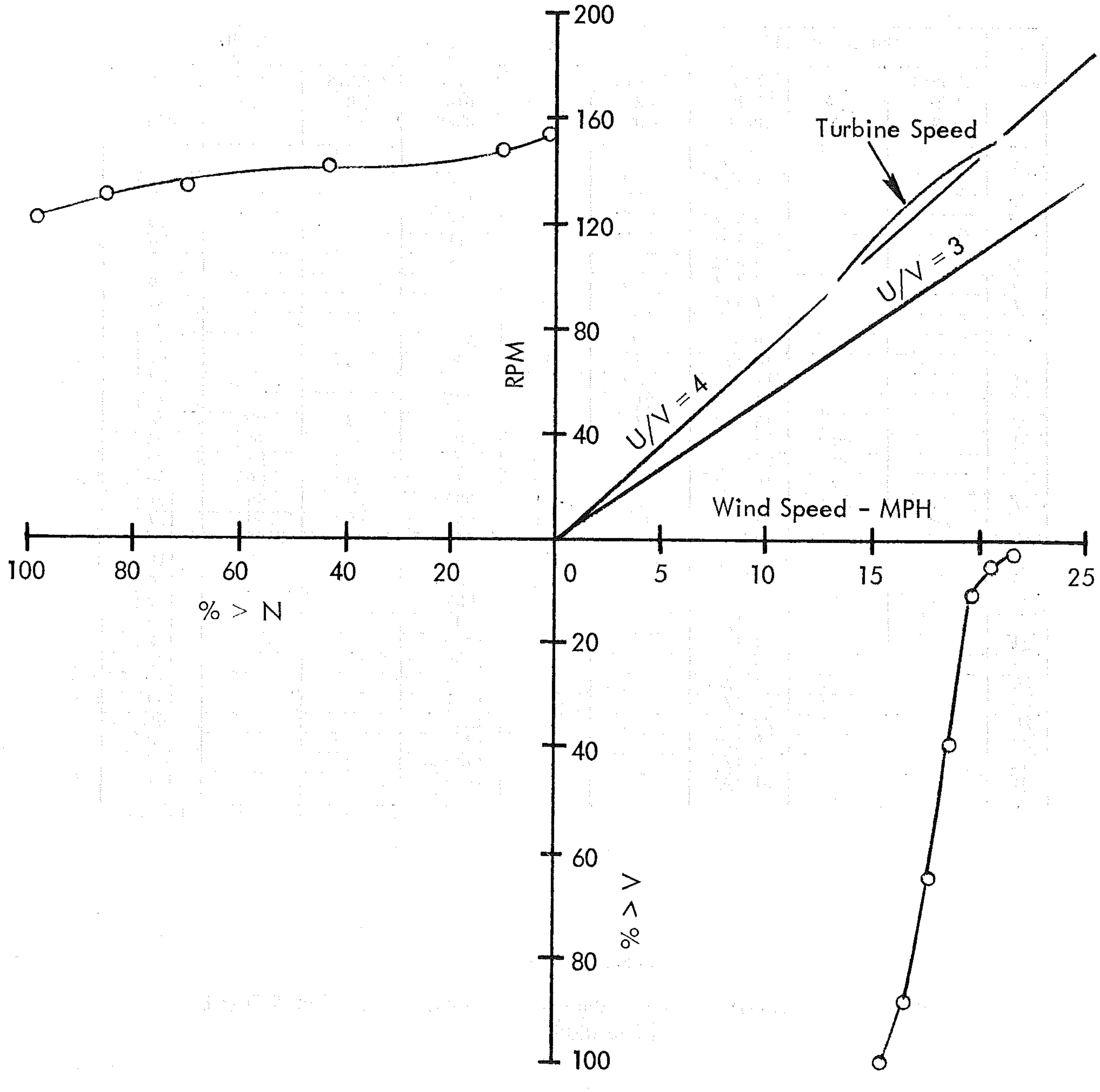
Table 8 (a)

System Performance from Compilator Data - Series 1 Tests (no-load)

| Bin # | WIND SPEED (V) | | | POWER (P) | | | RPM (N) | | |
|---|---|---|---|---|---|---|---|---|---|
| | COUNTS PER BIN | % > V | AVG. BIN SPEED | COUNTS PER BIN | % > P | AVG. BIN POWER | COUNTS PER BIN | % > N | AVG. BIN RPM |
| 0 | | | 1/2 | | | 23 | | | 4 |
| 1 | | | 1 1/2 | | | 70 | | | 9 |
| 2 | | | 2 1/2 | | | 117 | | | 14 |
| 3 | | | 3 1/2 | | | 164 | | | 20 |
| 4 | | | 4 1/2 | | | 211 | | | 26 |
| 5 | | | 5 1/2 | | | 258 | | | 32 |
| 6 | | | 6 1/2 | | | 305 | | | 38 |
| 7 | | | 7 1/2 | 5 | 98 | 352 | | | 43 |
| 8 | | | 8 1/2 | 7 | 95 | 398 | | | 49 |
| 9 | | | 9 1/2 | 3 | 94 | 445 | | | 55 |
| 10 | | | 10 1/2 | 5 | 92 | 492 | | | 61 |
| 11 | | | 11 1/2 | 8 | 89 | 539 | | | 67 |
| 12 | | | 12 1/2 | 21 | 81 | 586 | | | 72 |
| 13 | | | 13 1/2 | 22 | 73 | 633 | 8 | 97 | 78 |
| 14 | 1 | 99.6 | 14 1/2 | 31 | 61 | 680 | 15 | 91 | 84 |
| 15 | 3 | 99 | 15 1/2 | 30 | 49 | 727 | 21 | 84 | 90 |
| 16 | 6 | 96 | 16 1/2 | 45 | 32 | 773 | 40 | 69 | 96 |
| 17 | 20 | 89 | 17 1/2 | 37 | 18 | 820 | 38 | 55 | 101 |
| 18 | 28 | 79 | 18 1/2 | 36 | 4 | 867 | 65 | 30 | 107 |
| 19 | 48 | 61 | 19 1/2 | 11 | | 914 | 46 | 13 | 113 |
| 20 | 76 | 33 | 20 1/2 | | | 961 | 34 | 1 | 119 |
| 21 | 54 | 13 | 21 1/2 | | | 1007 | 2 | | 124 |
| 22 | 29 | 2 | 22 1/2 | | | 1055 | | | 130 |
| 23 | 4 | 4 | 23 1/2 | | | 1102 | | | 136 |
| 24 | 1 | | 24 1/2 | | | 1148 | | | 142 |
| 25 | | | 25 1/2 | | | 1195 | | | 148 |
| 26 | | | 26 1/2 | | | 1242 | | | 153 |
| 27 | | | 27 1/2 | | | 1289 | | | 159 |
| 28 | | | 28 1/2 | | | 1336 | | | 165 |
| 29 | | | 29 1/2 | | | 1382 | | | 170 |
| 30 | | | 30 1/2 | | | 1430 | | | 177 |
| 31 | | | 31 1/2 | | | 1476 | | | 182 |

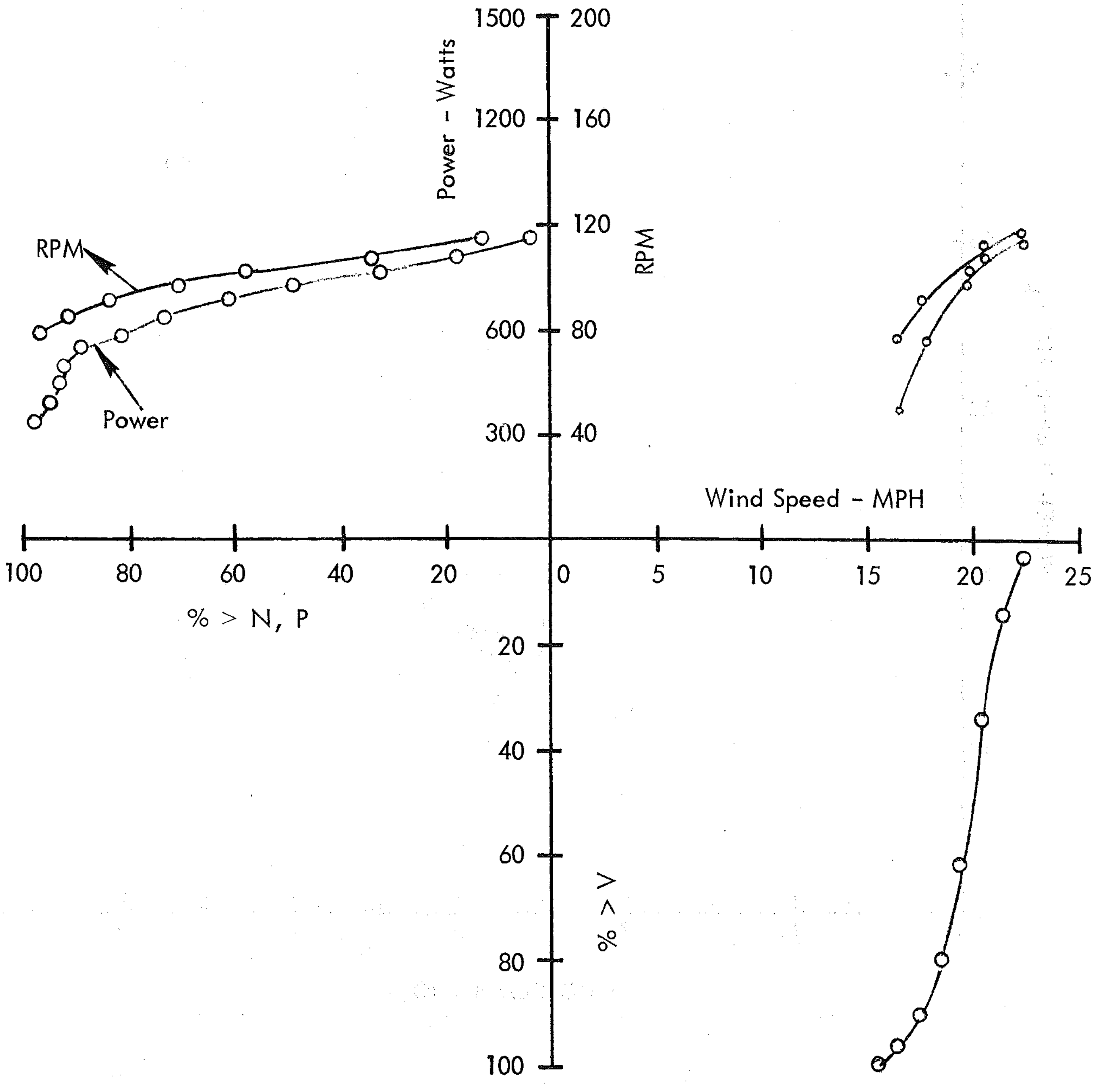
Table 8 (b)

System Performance from Compilator Data - Series 1 Tests (loaded)




a) No-Load; 5° Cyclic Pitch

Figure 34. System Performance from Compilator Data - Series I Tests.




b) Loaded; 5° Cyclic Pitch

Figure 34. System Performance from Compilator Data - Series I Tests (Concluded).

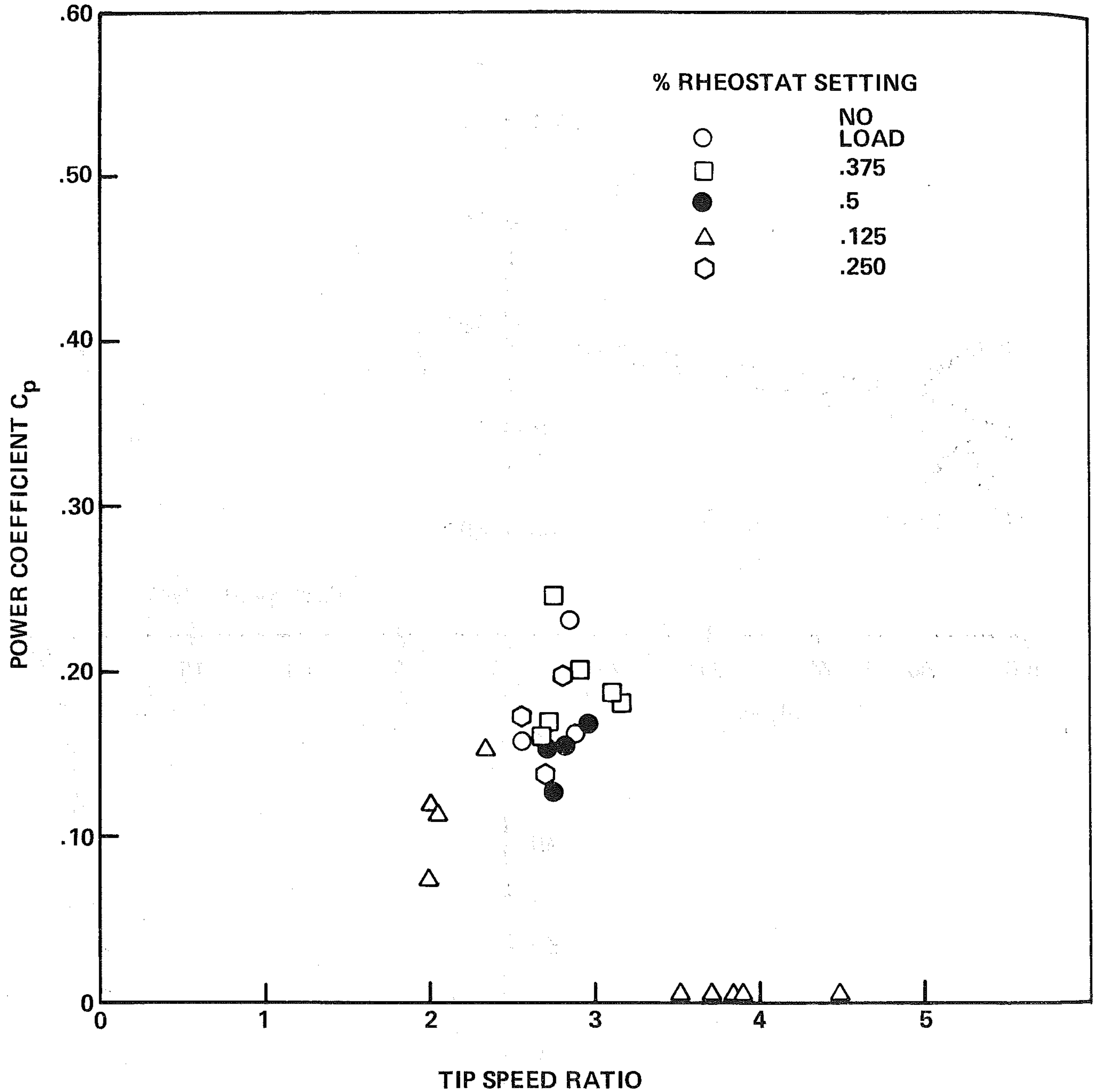



Figure 35. System Performance from Strip Chart Data – Series I Tests.

real wind as the forcing function. The most valuable test might be to monitor the output and field coil temperatures on a constant basis to ensure that they did not exceed an absolute design limit under any mode of operation.

When data were not available from the wind turbine, tests were run on the anemometry in an attempt to refine the wind speed estimate. Tests were run with three Maximum anemometers, one R. M. Young furnished by Rockwell and one 3-cup Belfort anemometer. The tests indicated that all of the anemometers had linear response over the ranges of wind speed observed. Therefore, all of the anemometers could be corrected to one another using a scaling equation. In summary, at 20 MPH, as determined by the Maximum anemometer on the 1-kW tower, the R. M. Young anemometer read 22 MPH and the Belfort, 19 MPH.

The latter part of the test period was to be used to gather additional performance data in order to evaluate the electrical system characteristics more fully. However, two problems hampered this effort. One was a lack of sufficient wind caused by a prolonged heat wave. The second was a technical problem which occurred in the electrical system.

It was noted that the electrical system output was constant at a low value of 100 watts. All wiring and the recorders were checked and found to be in proper order. The alternator was checked remotely and, although it appeared to be in working order, was a prime suspect for the error. Fuses were all right and the breadboard electrical system appeared to work satisfactorily during static checks. Investigation to uncover the problem was hampered by the poor wind conditions.

Sufficient running time was obtained in low winds to determine that the blades were getting out of adjustment and that noises indicative of improper clearance were occurring. A limited amount of data was also gathered on the control forces transmitted through the actuator rod. The machine was taken down on July 24. It was determined that the actuator control rod had backed off and caused the blades to be out of tune. All of the control system L-links required more room in the slots in the struts and the pull rods were hitting the struts. Modifications were planned to correct these conditions (see Sections 3.1.2 and 3.1.5). In addition, the gearbox showed signs of rust and the anodized aluminum surfaces had faded noticeably.

#### 5.2.2.2 SECOND SERIES

The first prototype equipped with modified blades (see Section 3.1.1) was reinstalled at the New Seabury test site at the end of July 1979. The blade leading edges had not been heat treated or anodized. A disk brake was still used for positive shutdown rather than an automatic system. The breadboard alternator was used on the turbine and the prototype electrical system except for the alternator lightning protection system was connected to the alternator. Instrumentation was the same as used in the first series of tests.

Poor wind conditions were encountered throughout most of the test period although winds up to 30 MPH were experienced for a short period. The limited data obtained indicated that the blade modification worked as expected producing positive forces on the control system, that is, the pull rods remained in tension. Also, the control forces were of the proper magnitude. A force of 120 lbs downward on the actuator rod was measured at 100 RPM (about 20 MPH wind) with the rotor unloaded. These forces were used to finalize the trip mechanism design.

Operation of the machine was noisier than expected. This was partly due to one blade being out of tune which resulted in an aerodynamic unbalance. The control actuator rod also began to loosen. The pull rod was striking the strut which could be corrected by proper shimming during subsequent installation.

Results indicated that the machine slowed down by reversing the blade pitch angle but the response was still sluggish. In addition, startup appeared sluggish. Both conditions were attributed to the need for more blade angle.

The limited test results also indicated that the aerodynamic wing used for the shutdown control of the machine was relatively ineffective. This result had been suspected during the first series of tests but was not verified at that time. It was not certain whether the effect was due to insufficient aerodynamic surface or to modified flow effects within the wake. It was decided to replace the tail/wing combination with a V-tail which would have more surface area and would extend above the machine's flow wake.

The turbine was removed from the tower on August 21. The rivets were removed from the blades and the modified leading edges were sent to be heat treated and anodized prior to reinstallation of the prototype with a V-tail.

### 5.2.2.3 THIRD SERIES

On October 29, 1979 the machine was reinstalled at New Seabury. The original tail vane/wing system had been replaced with a V-tail configuration (see Figure 1). It was also equipped with the Pinson trip mechanism which had been tested during the spin tests (see Section 5.2.5). The prototype electrical system, including the alternator, was connected to the turbine. The alternator lightning protection system was attached to the outside of the upper module of the tower. This location proved to be unsatisfactory because it was not possible to work at the box. The box should be located on the lower inside of the upper module so that the control box door can be opened and work done in connecting wires. The main control panel was also completed with the addition of a new dump load relay, a revised dump load PC board, and test points.

The weather for the most part was unseasonably calm during the test period with only two days in which moderate winds were encountered. The tower tests verified that the automatic control system on the turbine would shut down the machine and then reset at a lower wind speed. The machine was operated initially without weights on the Pinson trip mechanism. The control system tripped into the shutdown mode at approximately 120 RPM (about 20 MPH). It reset at a very low rotational speed. It was concluded that an additional five pounds of lead should be added as counterweight to the vane boom in order to adjust the trip mechanism so that shutdown would occur at a wind speed of about 30 MPH and restart at about 25 MPH. Shutdown at 30 MPH instead of the Phase I Final Design Review value of 40 MPH was selected for tower tests in order to keep the turbine operational range below the 3-per-rev excitation frequency at approximately 185 RPM. It was noted that the turbine was sluggish in starting even in winds of 12 MPH.

During subsequent tests, the winds gusted in excess of 35 MPH and were often too high for safe test conditions. It was verified that if the trip mechanism was set in the shutdown condition, it would remain that way in high winds, a necessary condition for the automatic control system. The high winds also produced a buffet condition on the V-vane which was best described as a Dutch-roll oscillation. It was noted that the vane mount on the boom did not provide sufficient tightness. Therefore, set screws were added to reduce the free play at the connection.

Tests were conducted in winds less than 15 MPH. The five pounds of lead were added to the V-vane boom. The sluggishness of the turbine in startup was verified. Considerable effort was made to retune the machine but the light wind made verification of the effect difficult. No electrical data were obtained.

During the test period, Pinson installed a commercial 16-ft turbine equipped with a collective control system at their facility. It was observed that this machine began to operate in a 5 MPH wind. This verified that the low solidity of the similar 1-kW machine was not the cause of the sluggishness. It was felt that the control system was the source of the problem.

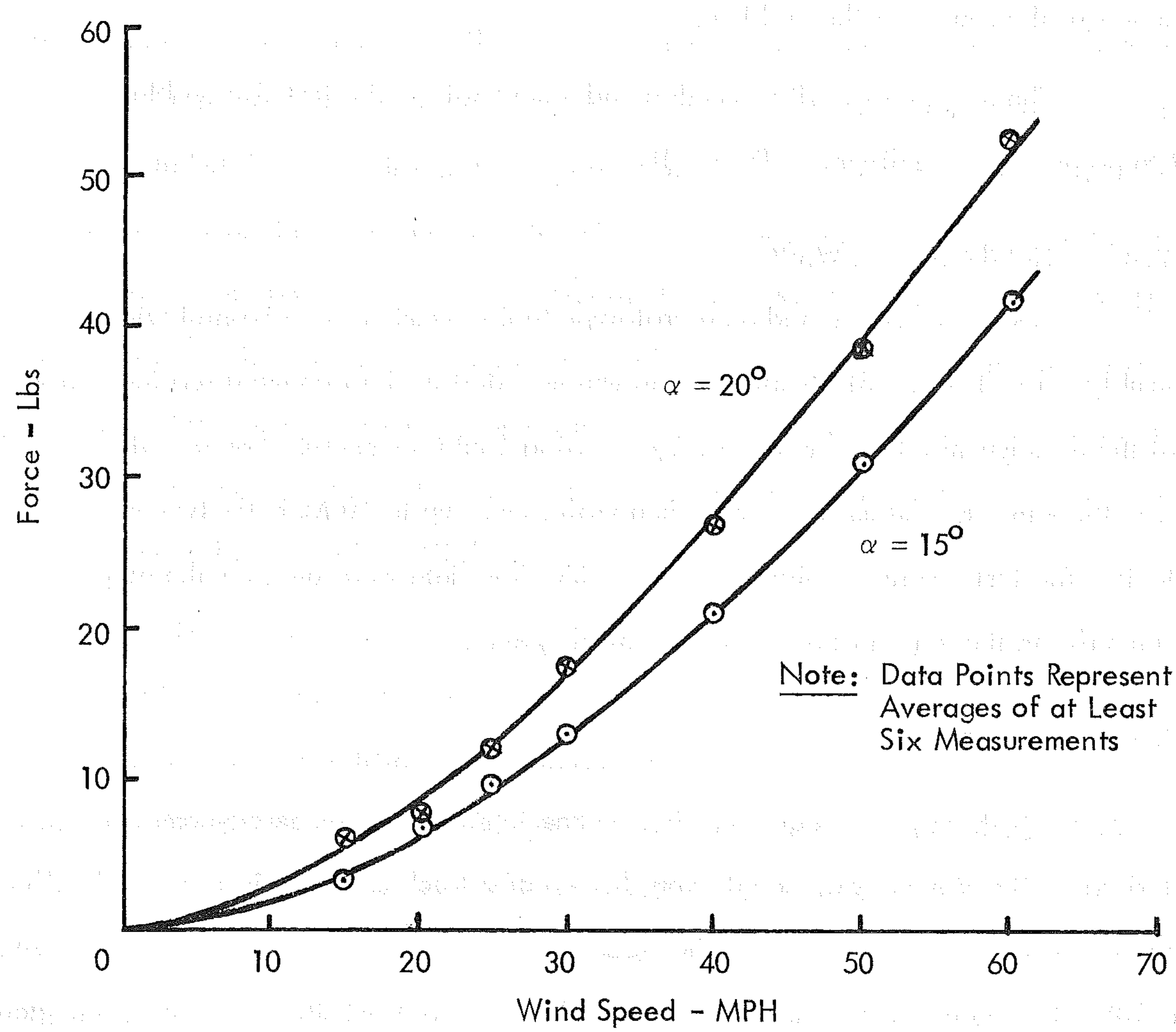
The machine was disassembled and removed from the test site on November 19 to prepare it for delivery to Rockwell.

### 5.2.3 HORIZONTAL WING

Tests were conducted on a prototype highly cambered horizontal wing assembly. The 1 x 4 foot aluminum wing was mounted six feet above a service van so that the aerodynamic force generated by the wing could be measured on a scale located inside the van. Measurements were taken with speeds up to 60 MPH for two angles of attack. The test results are shown in Figure 36. The data were used for the purpose of integrating the wing in the tilt-cam control system.

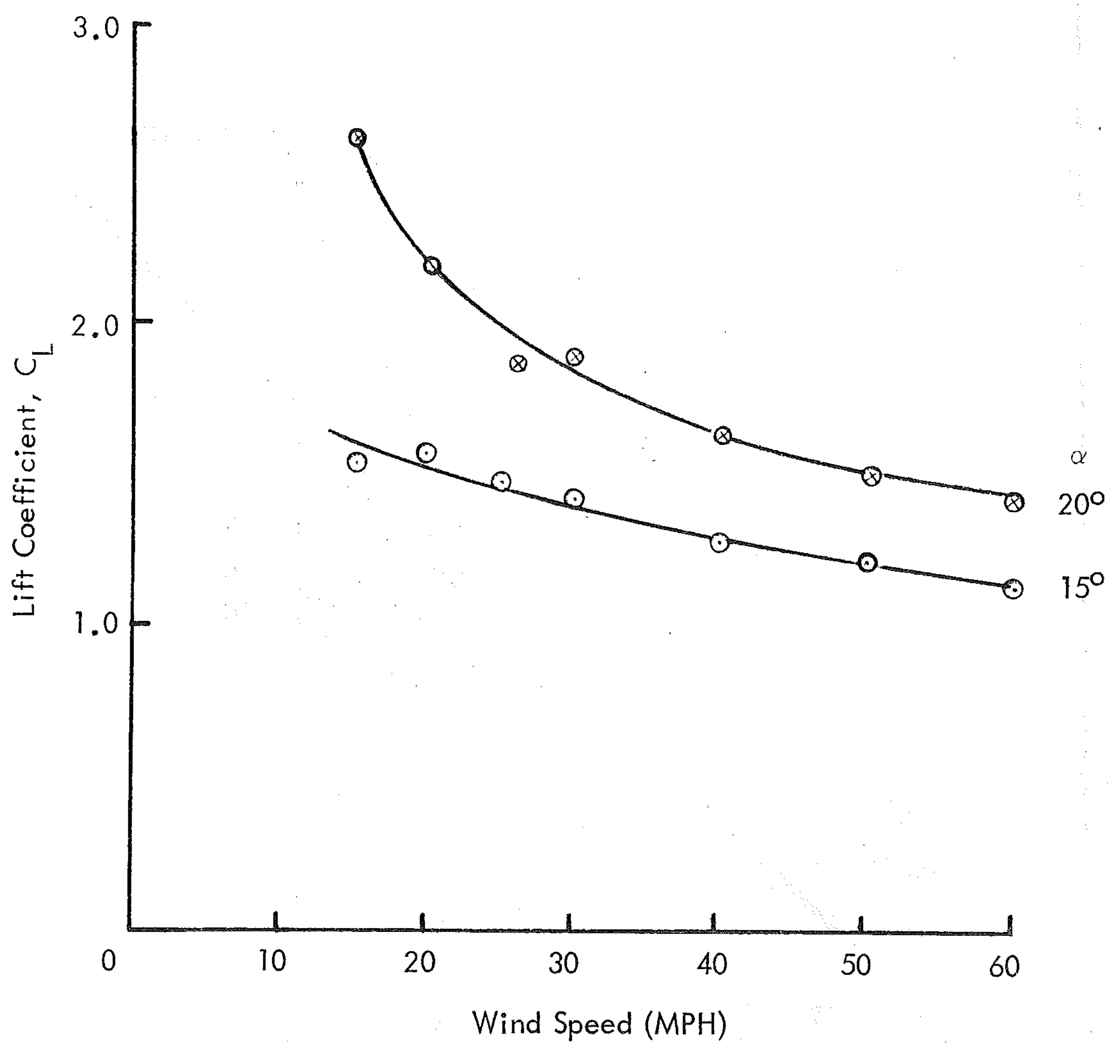
### 5.2.4 V-VANE

Tests were conducted on the V-vane to determine its aerodynamic lift characteristics. The V-vane was mounted on the top of a truck as shown in Figure 37. The vane was tufted in order to observe the flow pattern on the underside of the vane (see Figure 10). Force on the V-vane was transmitted inside the truck through a rod connected to a scale system. A series of runs were conducted at speeds up to 35 MPH. Flow over the vane appeared to be smooth. Initial tests were repeated since wind gusts were encountered. Data obtained during the tests are included in Figure 38. It was concluded



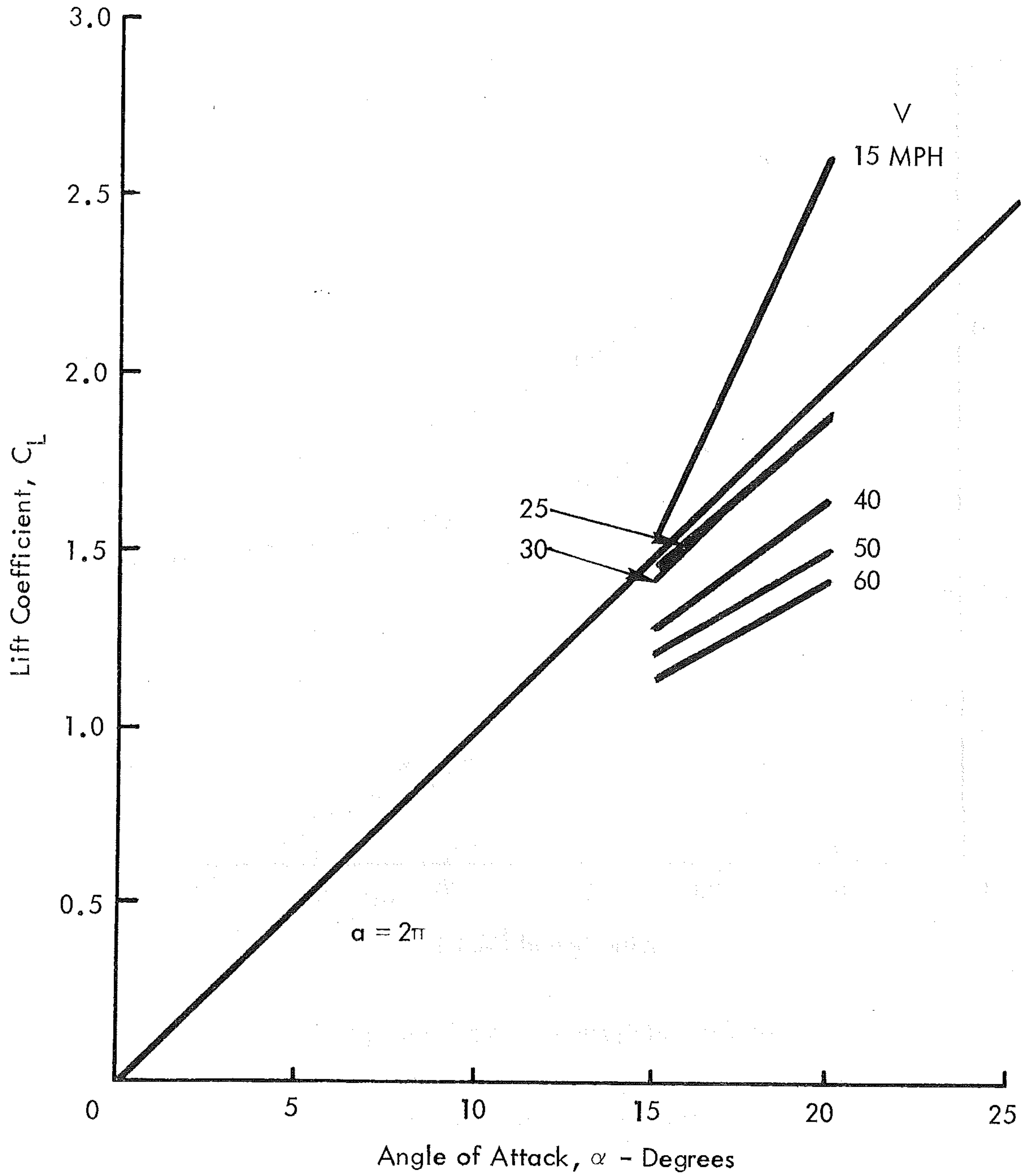

a) Force versus Wind Speed

Figure 36. Aerodynamic Data for Control System Horizontal Wing.




b) Lift Coefficient versus Wind Speed

Figure 36. Aerodynamic Data for Control System Horizontal Wing (Continued).




c) Lift Coefficient versus Angle of Attack

Figure 36. Aerodynamic Data for Control System Horizontal Wing (Concluded).

Figure 37. Test Setup for V-Vane.

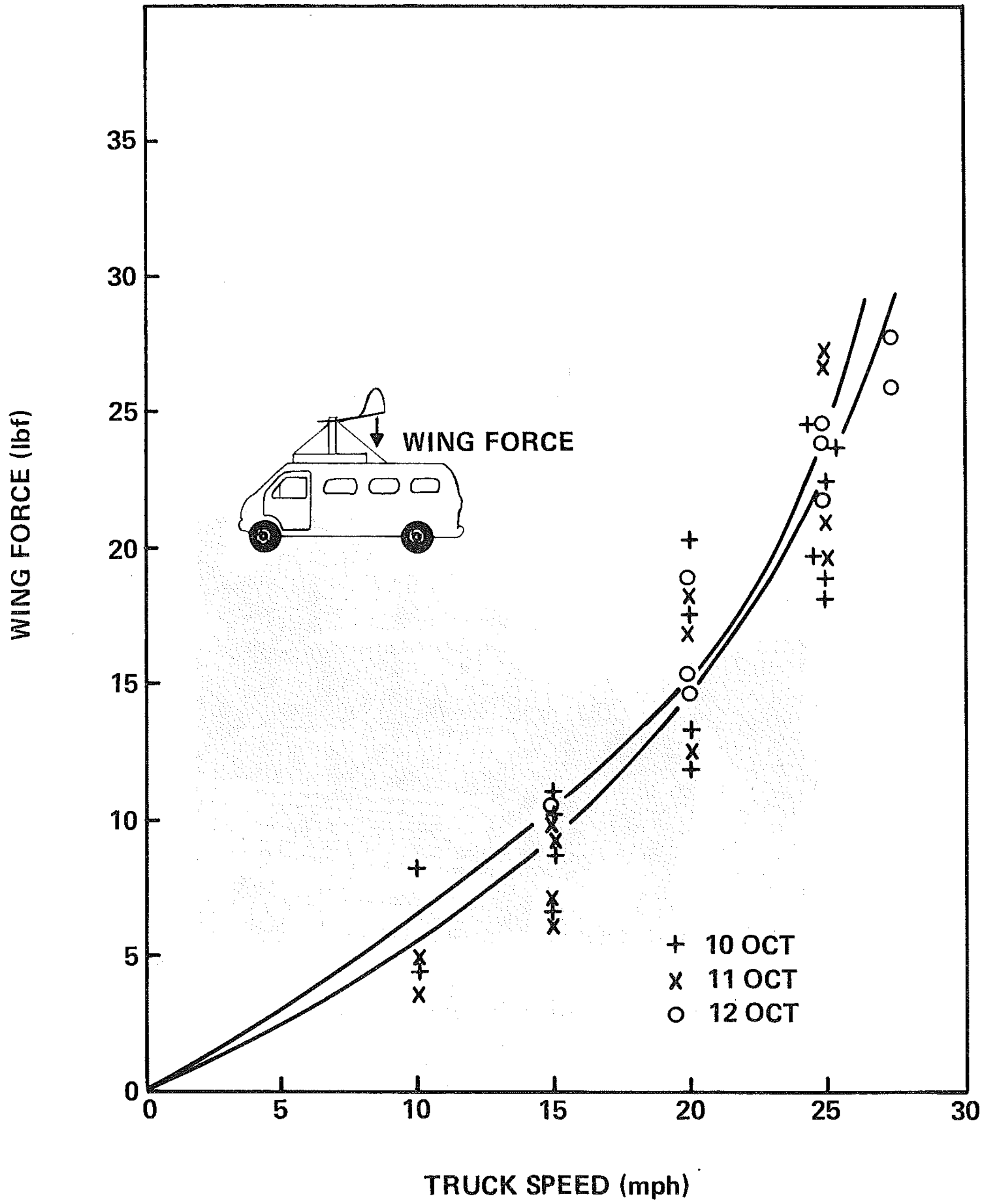



Figure 38. Aerodynamic Data for V-Vane.

that the vane was more effective than the vane/wing system and would provide the required control forces.

### 5.2.5 SPIN

Spin tests were conducted to determine the effect of RPM and tilt-cam angle on the control forces and to verify that the Pinson trip mechanism would be properly activated by the control actuator rod. A special concrete pad was poured and a spin test stand erected which was similar to the top section of an Octahedron tower. The tower top adapter/bearing cartridge and main shaft of the first prototype were mounted on the spin stand. The struts were fastened to the hubs. A Powertron motor to spin the turbine was mounted onto the spin stand. A Fincor motor control unit was used to run the motor at various speeds. Variable control of the motor permitted accurate determination of the control loads as a function of RPM.

The spin test setup was checked out by spinning the machine without blades. The initial test revealed that the ratio of the first prototype gearbox was too high for the RPM range of the motor so that the machine only turned at slow speed. Therefore, the transmission was replaced with the 15:1 gearbox originally purchased for the prototype.

The tilt cam, blade, and V-tail vane were then assembled (see Figure 39). The blades were cut out around the blade/strut connection to provide additional clearance to permit rotation of the blade without striking the strut (see Figure 7). The blades were also cut out on the outer surfaces at the connections to allow access for installation of the blades. The pull rods were connected to the blades with shims carefully added to prevent binding (see Section 5.2.2.2 and Figure 8). The tilt cam was connected to the actuator rod passing down through the main shaft. The connector at the lower end of the shaft was modified to prevent the rod from turning loose. The strain gauge beam used in

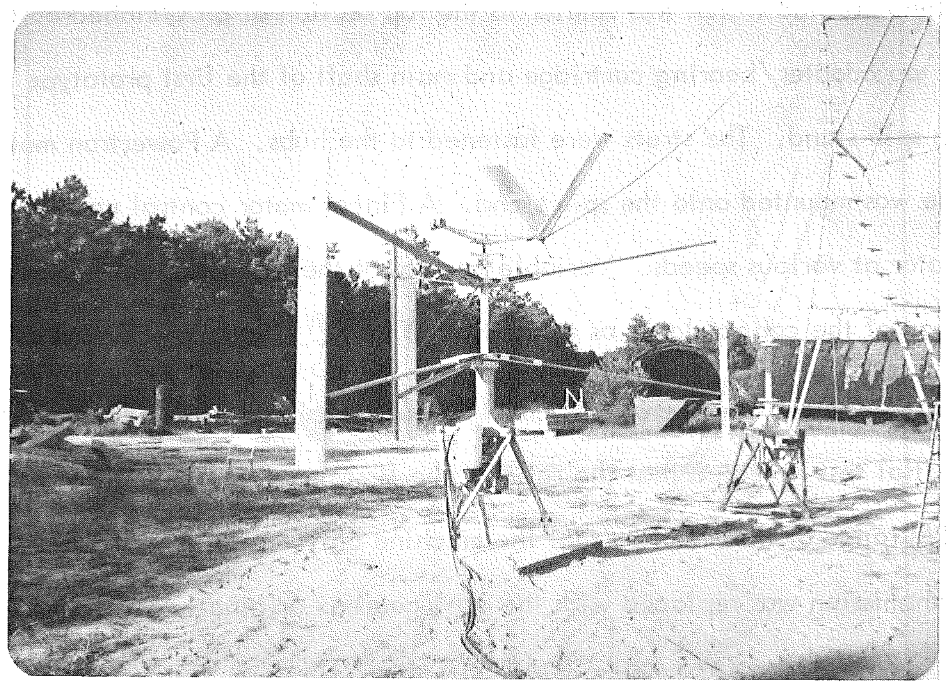


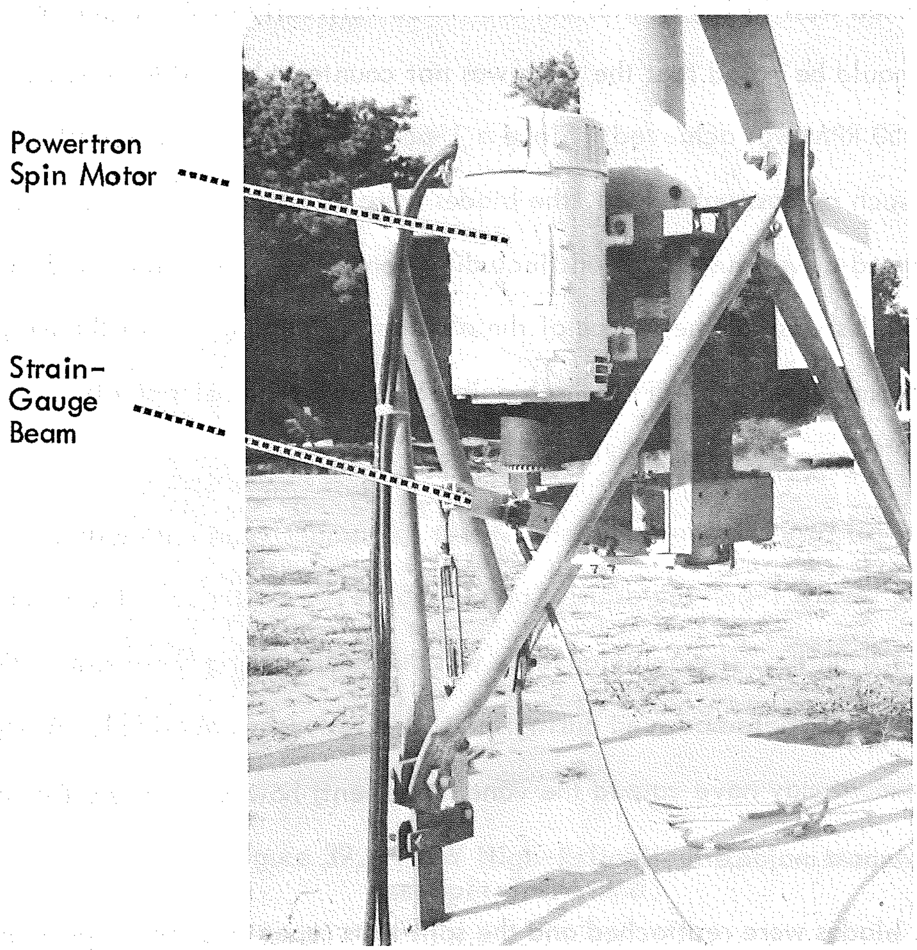
Figure 39. 1-kW High-Reliability Turbine Mounted on Spin-Test Stand.

tower tests (see Section 5.2.2) was connected to the lower end of the actuator rod and mounted so that force in the rod could be measured (see Figure 40).

Spin tests were made and RPM determined visually with the aid of a stop watch. The machine operated smoothly although one blade appeared to be out of tune. The V-vane tracked well in light winds but oscillated vertically at the 1-per-rev frequency. It should be noted that the vane was not counterbalanced for this test. A maximum of 150 RPM was achieved. Since a 1-per-rev oscillation is usually due to inertial effects such as mass unbalance, the blades were suspect. It was noted that the oscillation occurred at various conditions including zero pitch which indicated that cycling of the blades was not the source of the problem. It was seen that the magnitude of the oscillation increased with RPM which pointed to a mass unbalance effect. It was discovered that similar results had occurred on the tower tests.

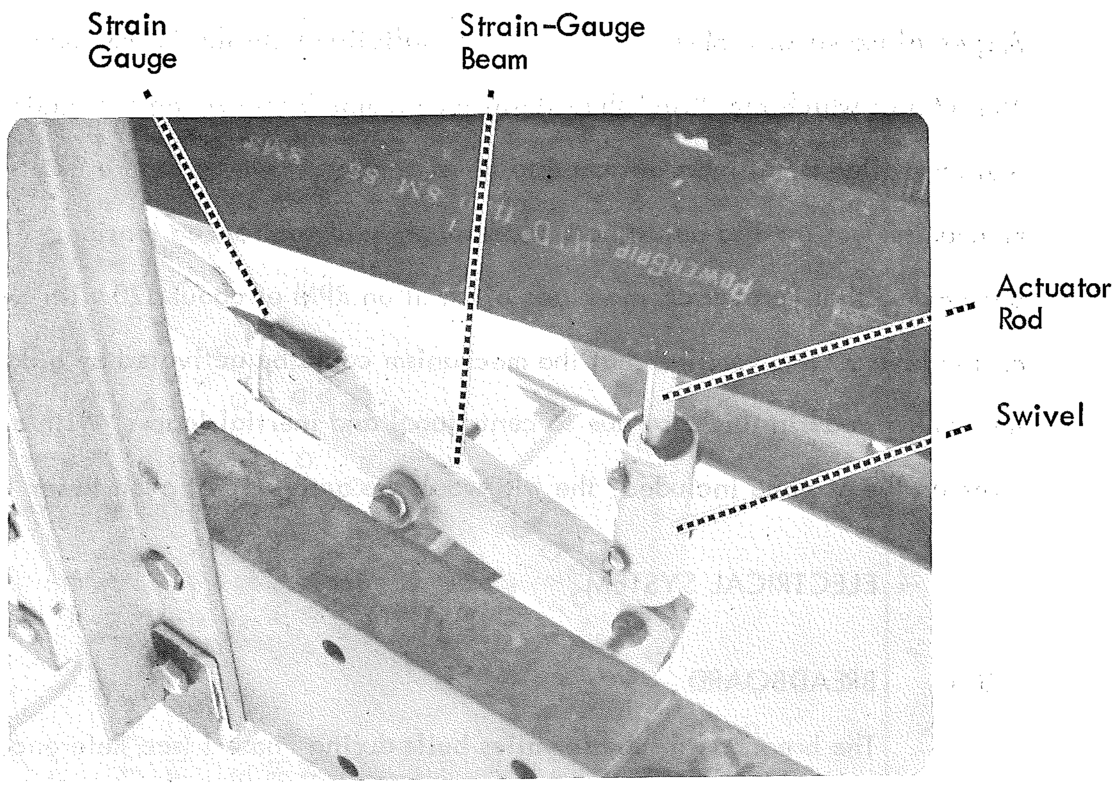
Spin tests were conducted then without the blades, and both with and without the V-vane. The severe 1-per-rev oscillation was not present although, the vane, when included, did move slightly. The actuator force was measured during these tests. Positive control loads similar to those observed during the tower tests were obtained. A slight wobble due to shaft alignment may have caused the vane movement; however, it was felt that blade unbalance was a major effect.

The blades were reattached and the spin tests repeated. The 1-per-rev oscillation occurred with a couble amplitude equivalent to approximately 75 percent of the mean loading on the actuator control rod. From these tests, it was determined that the blades were out of balance so that if one blade was taken as the norm, then one produced a nose-heavy pitching moment and the other produced a tail-heavy pitching moment.




a) Test Setup

Figure 40. Strain-Gauge Beam for Spin Test.




b) Actuator Rod Swivel Connector and Beam.

Figure 40. Strain-Gauge Beam for Spin Test (Concluded).

The blades were removed and modified to permit mass balancing (see Section 3.1.1). Subsequent to balancing, the blades were reinstalled and spin tests conducted. The 1-per-rev oscillation was effectively eliminated. Data recorded for the turbine with and without the tail vane are presented in Figure 41.

A final series of spin tests were run with a Pinson trip mechanism installed. A special mount was fabricated to allow installation with the Powertron spin motor. The RPM at which the "trip" shuts down the turbine by reversing the blade pitch angle was controlled by weights attached to lever arms as shown in Figure 42. The trip mechanism was used to adjust both blade angle and control rod tension. The trip was adjusted so that it reversed the blade pitch at an RPM of about 120 with five pound weights on the lever. This verified that the mechanism could be activated by a down load on the control rod, in this case due to centrifugal and inertial loads. With aerodynamic force on the V-vane included, the trip would be activated at even lower RPM.

## 5.3 ELECTRICAL SYSTEM

### 5.3.1 BREADBOARD

The breadboard subassemblies built during Phase I (see Reference 2) were assembled into a system. The basic NPI alternator was rewound into the 1-kW configuration. The system electronics underwent a short burn-in period and the alternator power characteristics were determined.

Performance tests using the power rectifier, voltage regulator, and the alternator were conducted. The test setups are included in Figure 43. In the first part of each test, the voltage regulator was included (Figure 43a). A check was made to see where the alternator self-excited and if the system limited the battery voltage to 28 volts. The prototype system excited well below the desired cut-in speed and the control

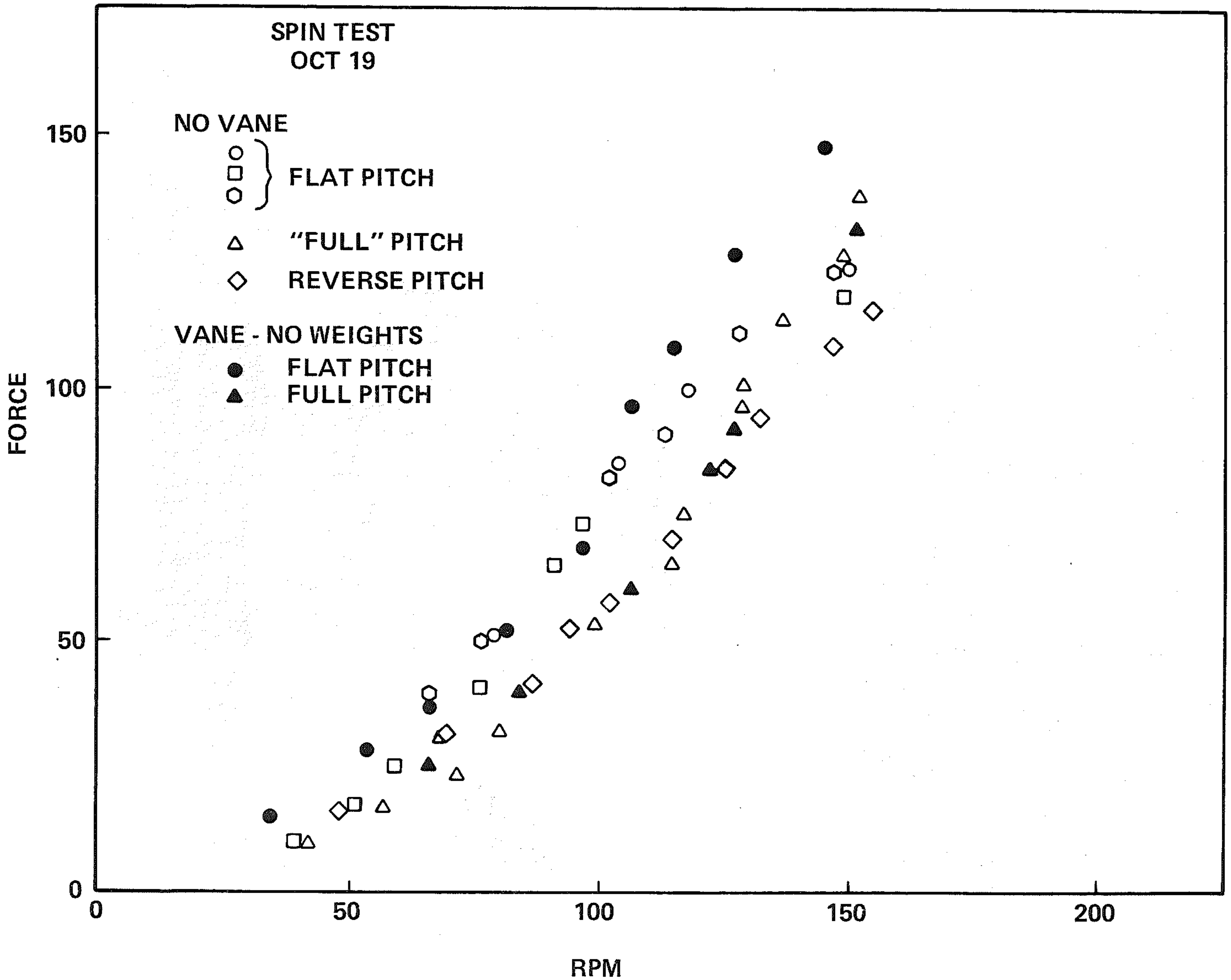
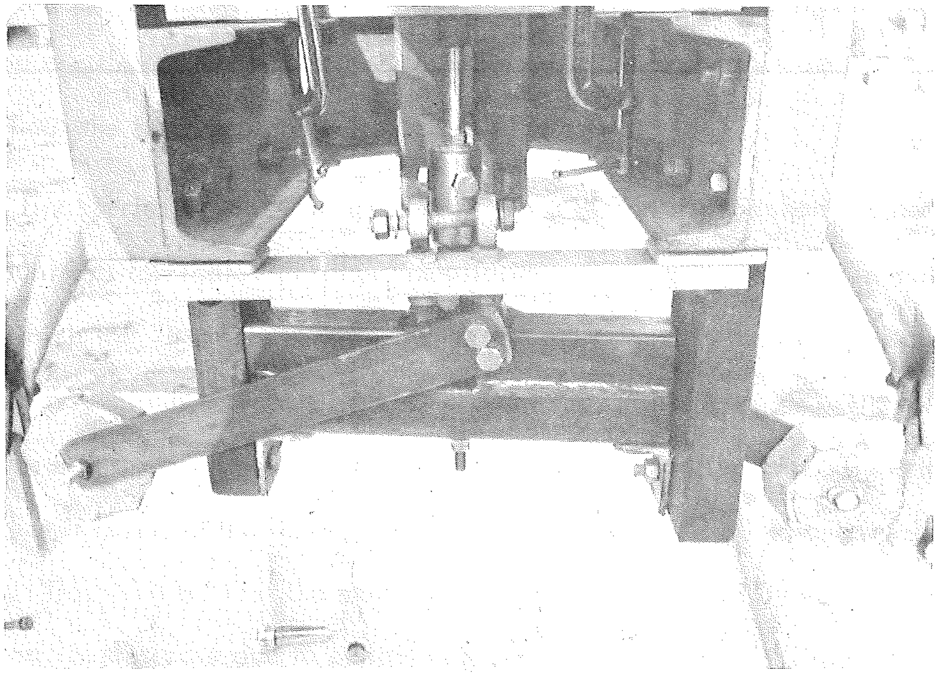
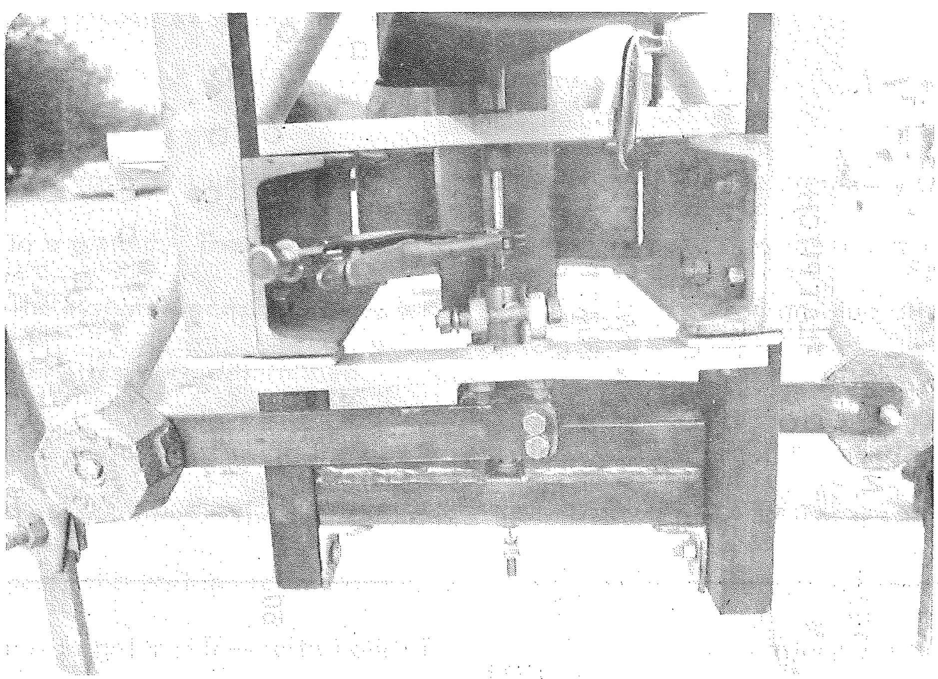



Figure 41. Control Force in Actuator Rod - Spin Tests.

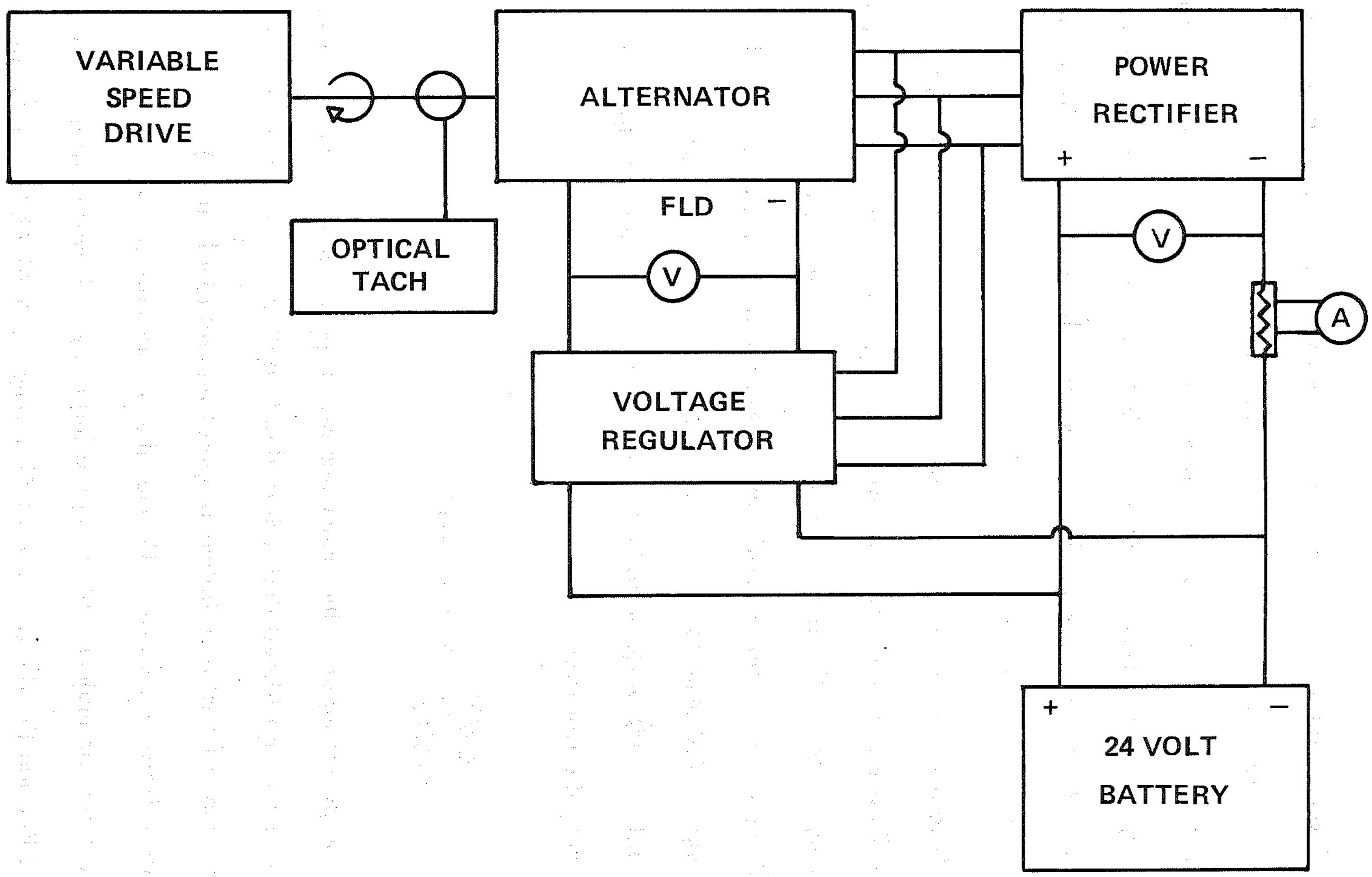


a) Operating Position



b) Shutdown Position

Figure 42. Pinson Trip Mechanism with 5 Lb Counterweights - Spin Tests.




a) Voltage Regulator

Figure 43. Breadboard Electrical System Test Setup.

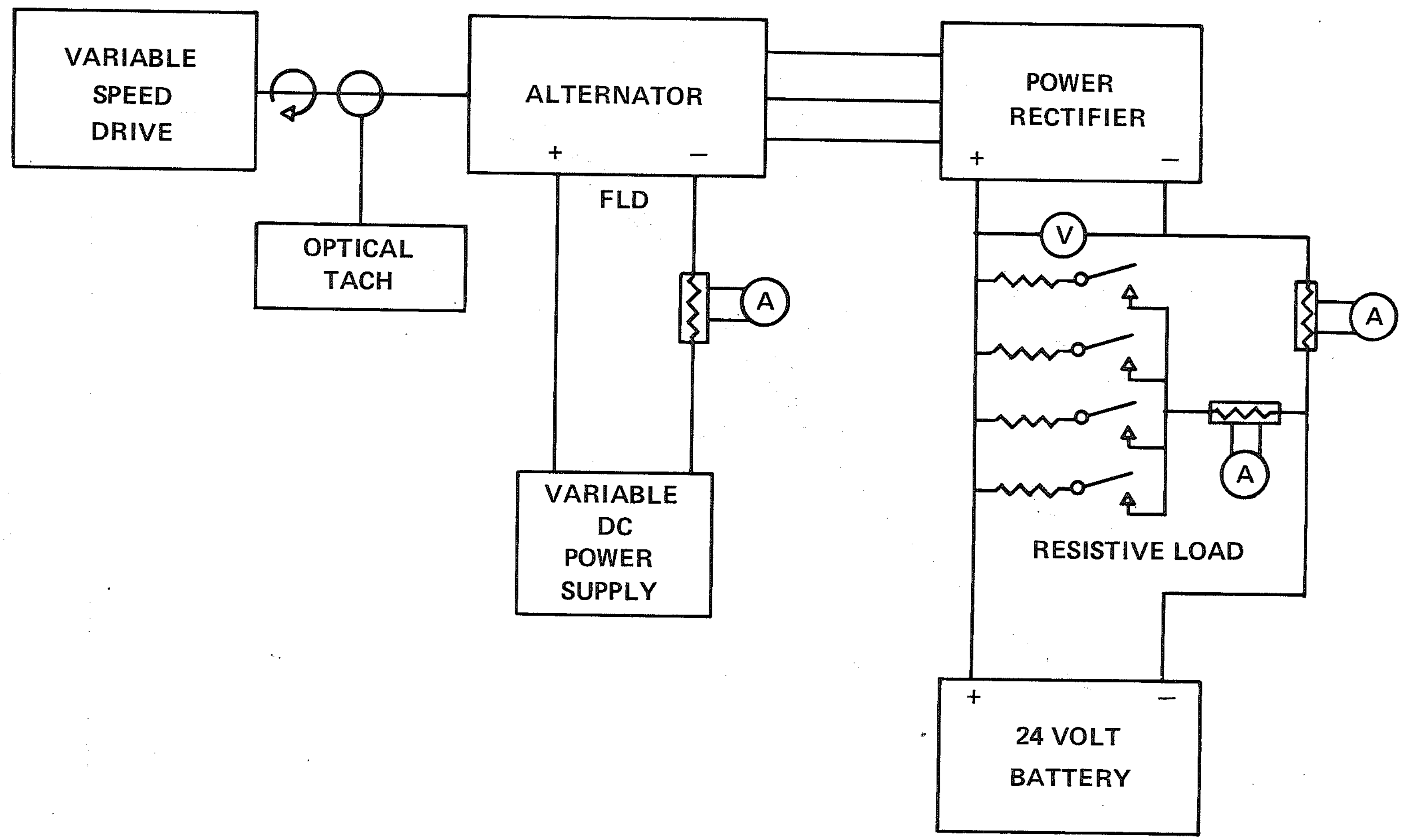
system limited the battery voltage to 28 ± 0.1 voltages over the full operating range of the alternator.

The alternator output tests (Figure 43b) were conducted at 26 V DC. This voltage was maintained by switching a resistive load in parallel with the battery pack. A slightly different characteristic would have been obtained without the constant voltage and energy storage characteristics of the battery (i.e., the resistive load alone). The primary reason for the resistive load was to prevent the load voltage from increasing during the course of the test due to the battery becoming charged.

Before the output tests were conducted, the alternator was allowed to run 1/2 hour at 20 amps output. This was to ensure the alternator was near its normal operating temperature. The first test was run with an alternator wound with 10 turns of AWG 12 copper on its output coils and 2100 amp-turns on the field coil (3 lbs of AWG 20 copper, 9.8 ohms @ $25^{\circ}$ C). The results of this test are shown in Figure 44(a). A design point of 1100 watts of 2670 RPM was chosen. An ideal output curve was generated using the relation

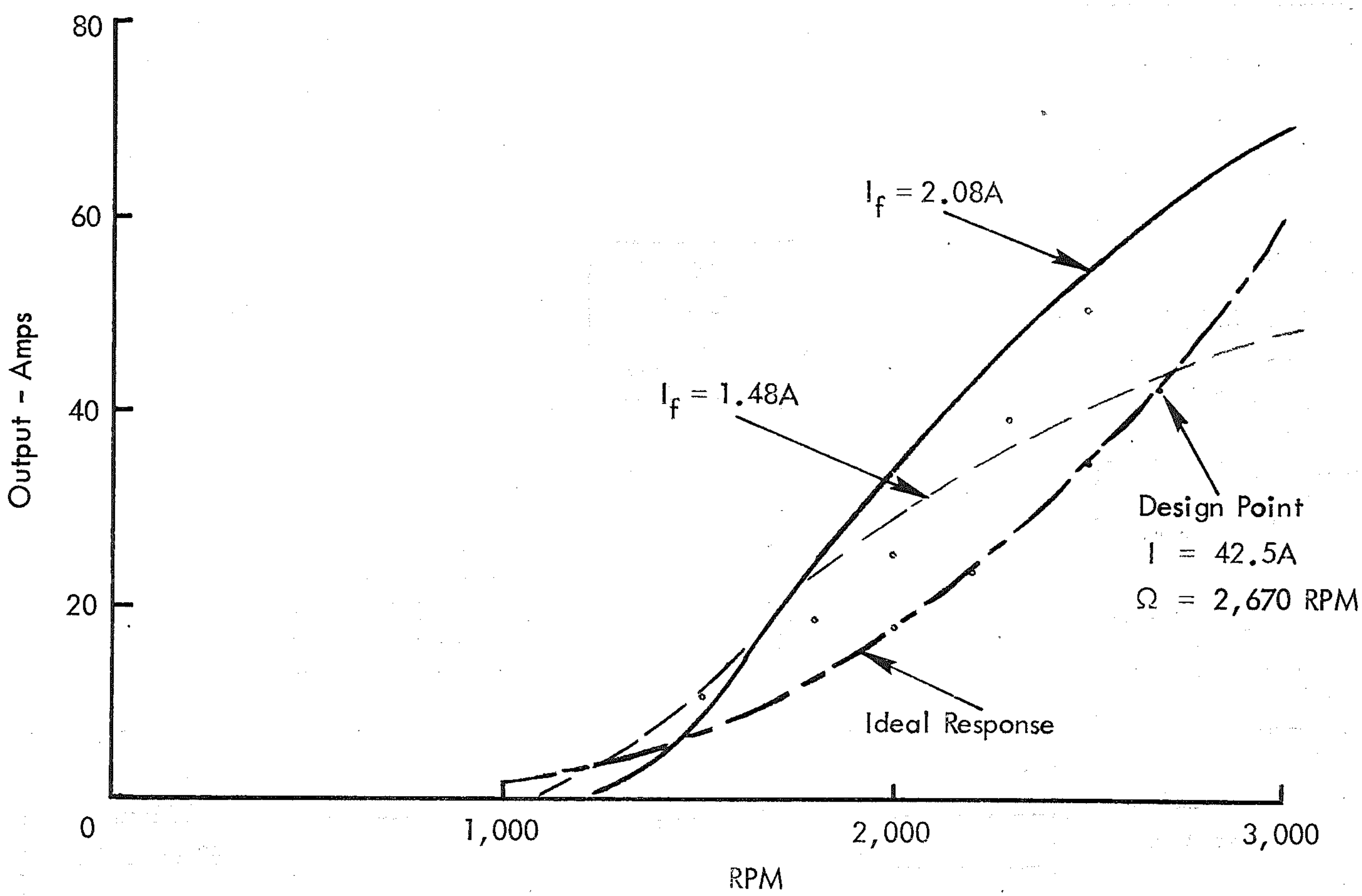
$$\left(\frac{\text{RPM}}{2670}\right)^3 \times 42.3 \text{ amps}$$

The power input to the generator was of prime concern as it relates to turbine loading, but it was considered that detailed calculations of the above were not warranted until the best shape (least area between operating and ideal curve) was selected. It was noted that for a field current of 2.36 amps the output current exceeded the desired response curve for the majority of the operating range. It was possible to drive the output curve through the design point of 42.3 amps @ 2670 RPM by reducing the field current to 1.48 amps. It was desirable to reduce the slope of the output curve to obtain a better match to the power available from the turbine.




b) Output versus RPM

Figure 43. Breadboard Electrical System Test Setup (Concluded).



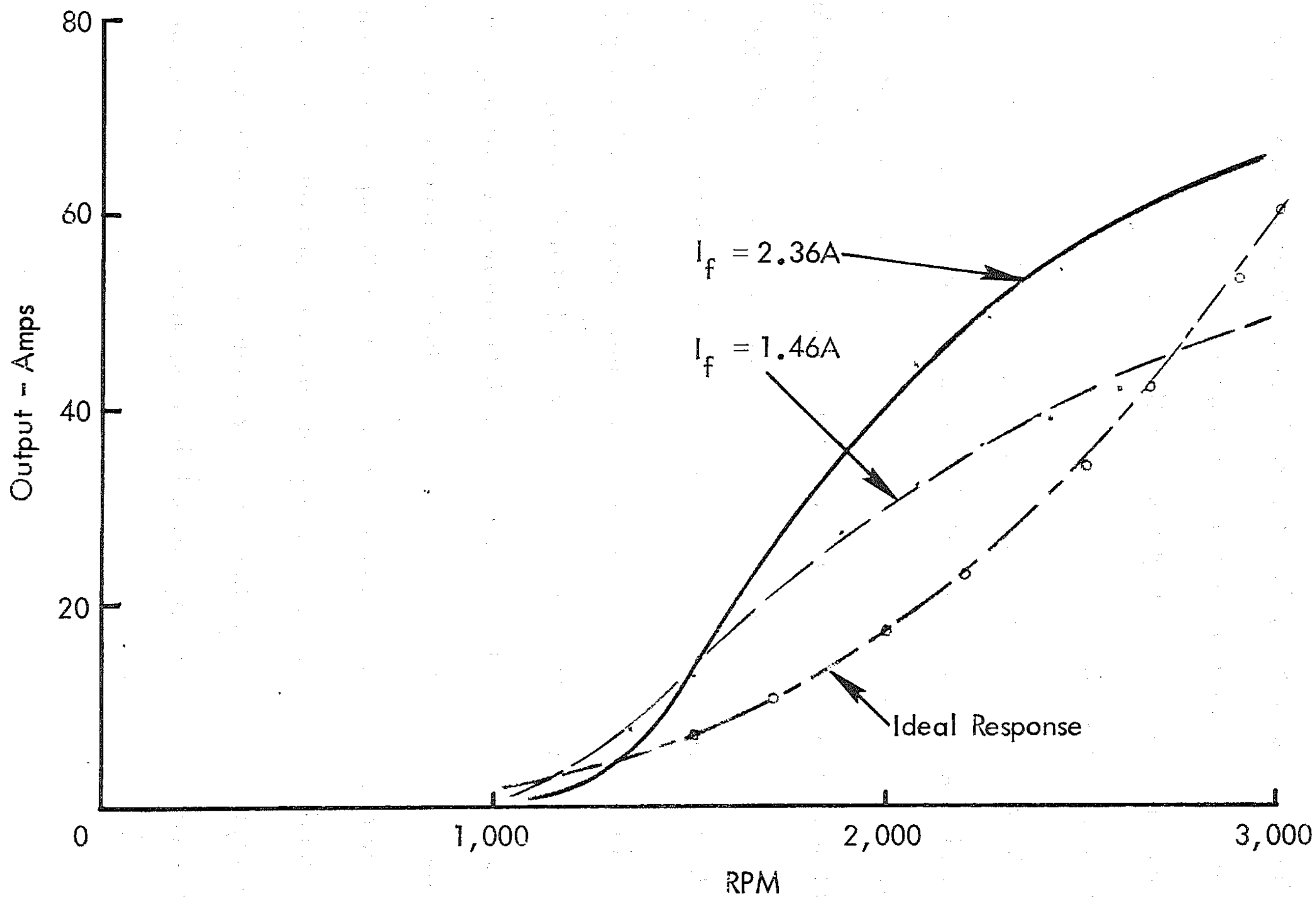

a) 10 Turns

Figure 44. NPI Breadboard Alternator Performance.

Therefore, a second alternator was wound with 11 turns of AWG 12 wire on the output coils. The aim was to reduce the slope of the output current by adding a turn. The additional turn provided 11/10 times the EMF, which tended to steepen the output curve. The additional turn also was to add approximately $(11/10)^2$ as much inductance which was a major determinate of the alternator's performance. The second test results shown in Figure 44(b) show that adding an additional turn of wire to the output coils was not the correct approach. It appears that the effect of the inductance was felt by the alternator only at higher speeds (frequency), but the output coil EMF was dominant at the lower speeds.

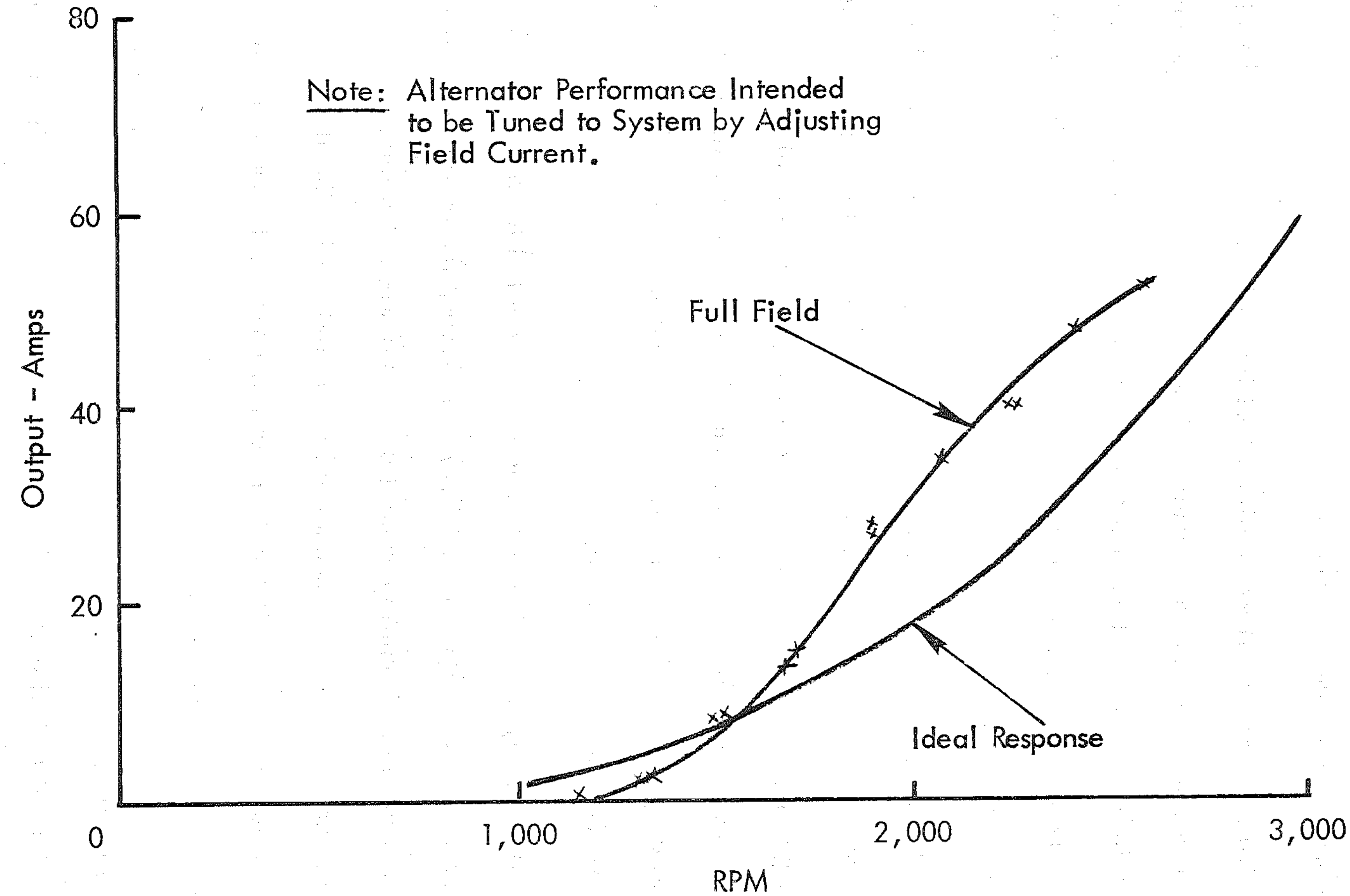
A third alternator was wound with 9 turns of AWG 12 copper wire on its output coils and 2100 amp-turns of AWG 21 copper on the field coils. Results for this alternator are given in Figure 44(c). This acted to reduce the slope of the output current at low speeds and steepen the current slope at the higher speeds. This provided a better match to the wind turbine. This version was selected for use in the prototype based on the test results, and was used in prototype machine testing (see Section 5.2.2).

During the first series of prototype machine tests at New Seabury (see Section 5.2.2.1), problems were detected in the breadboard electrical system. It was determined that a diode in the voltage regulator circuit had blown, apparently from a surge overload. During the prototype tests, the machine had been unloaded by removing the fuse from the electrical system. This sent a surge voltage through the components which apparently caused the diode to fail. This procedure was not used in subsequent tests. The terminals on the breadboard alternator were badly corroded and so were replaced with brass terminals of the same type as will be used on the prototype machines.




b) 11 Turns

Figure 44. NPI Breadboard Alternator Performance (Continued).




c) 9 Turns

Figure 44. NPI Breadboard Alternator Performance (Concluded).

### 5.3.2 PROTOTYPE

Testing of the breadboard version of the electrical system in the laboratory and as part of the prototype machine tests aided in the verification of the design prior to incorporation in the first prototype. Tests of the prototype electrical system were limited to burn-in and function checks.

During burn-in, it was noticed that the series inductors in the alternator lightning protection network were running at 60°C above ambient temperature. This exceeded reliable operating temperatures. To remedy this situation, the series inductors that handle the output power of the alternator were hand wound using a heavier gauge wire (see Section 3.2.2).

The prototype alternator was bench checked and then hooked up to the main control panel. No problems were detected. The main control panel was also hooked up to the lightning protection system. A filter capacitor was noted to be not working properly. It was replaced. Tests of the dump load circuit indicated that the PC board was not wired correctly. The board was corrected and delivered for the third series of machine tests (see Section 5.2.2.3).

The prototype electrical system was connected to the turbine for the second series of tower tests (see Section 5.2.2.2). However, the breadboard alternator was used and the alternator lightning protection circuit was not included. The complete prototype electrical system was connected to the turbine for the third series of prototype tests (see Section 5.2.2.3). The system was not completely checked out during these tests due to poor wind conditions.

## 5.4 MANUAL INSTALLATION

Manual installation of the first prototype on the 42.5-ft Octahedron tower was specified by Rockwell in Phase II (see Section 3.3.2). A davit mounted on the tower and controlled by ropes was selected as the means of manual installation. A davit owned by Pinson and used for manual installation of their commercial machines was selected as the initial version. It was noted, however, that the first prototype 1-kW turbine weighed more than the commercial machines. During the attempt to hoist the prototype weldment onto the tower by means of the davit, it was evident that excessive stretch in the ropes due to the weight of the weldment made control of the davit very difficult. Then, after hoisting the weldment a short distance, one arm of the davit began to buckle. The test was then cancelled.

An aluminum davit to hoist the complete 1-kW turbine was designed and built. It consisted of a long vertical boom attached to the tower and was composed of two tubes welded together with internal ferrule. The crane portion of the davit was a tube mounted at $90^{\circ}$ to the boom, and which could swivel. The load was hoisted by pulleys and cables controlled by a winch which could be operated either manually or electrically.

Prior to the test, it was noted that the junction of the upper and lower tube sections of the davit was not assembled correctly by the welder. However, it was decided to attempt a hoist with the davit as delivered. The davit was installed in about 1-1/2 hours which was significantly faster than previous davits. A Cycloturbine C2E bearing cartridge and shaft with attached weights was used as the test weight. The combined weight was about 400 lbs. A tie-line was attached to the hoist weight in order to prevent the weight from striking the tower. Two men were on the tie-line and one man operated the winch.

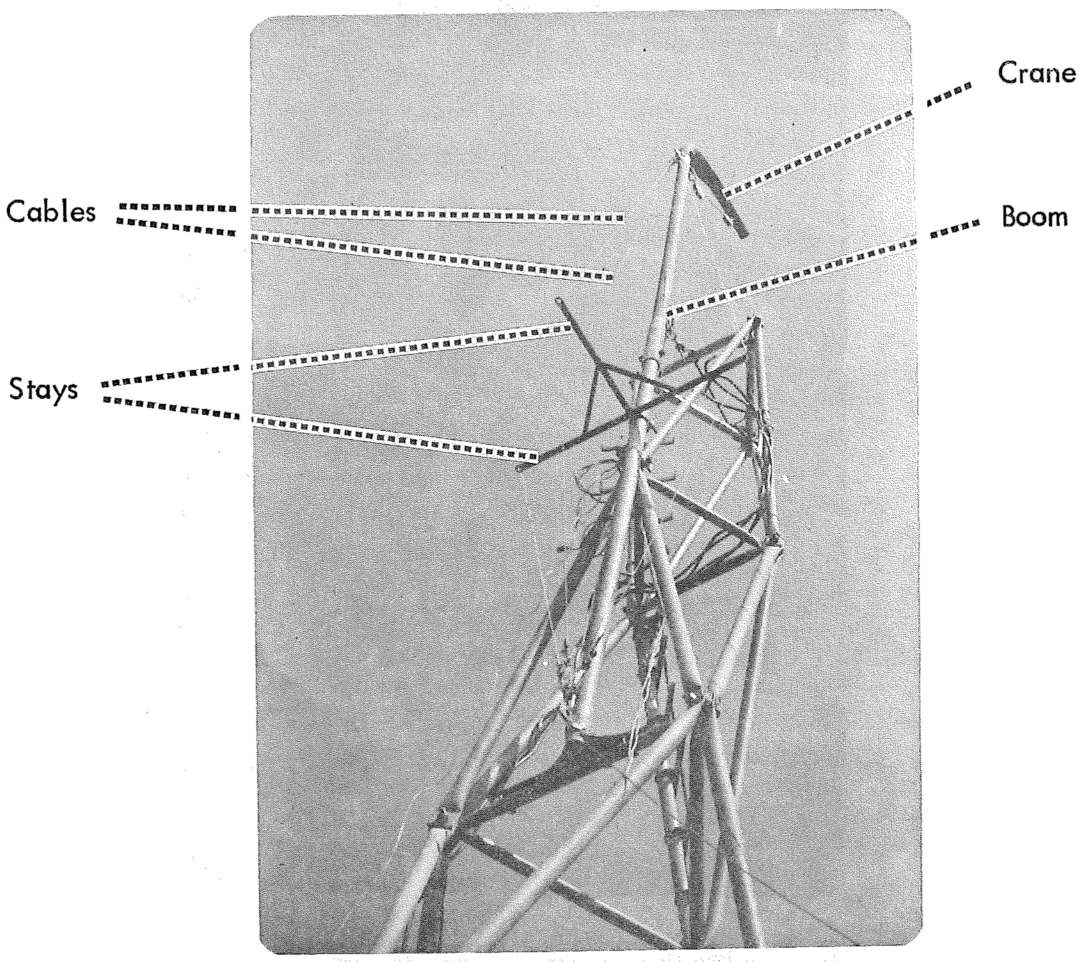
The davit was sufficiently strong to lift the weight; however, the crane tended to rotate and was difficult to control. The tie-line men allowed the crane to rotate slowly to determine how difficult it would be to prevent the weight from swiveling. The load was rotated about $30^{\circ}$ from the original position with no apparent difficulty in restraining the swiveling. However, at this point, the crane began to increase in rotational speed and the tie-line men were unable to prevent the swiveling of the crane. The crane continued to swivel uncontrolled. Then the vertical member failed at the junction of the lower and upper tubes. This was the area improperly assembled at the welding shop.

The davit was redesigned to improve its strength and ease of installation, and to eliminate the swivel feature of the crane. The redesigned davit was fabricated from steel to keep its cost low since it was to be a prototype of the version sent to Rockwell. Figure 45(a) shows the davit in position on the tower. Stays and cables are shown which increase the bending strength of the boom. The hand/electric winch for hoisting was attached to the rear of a pickup truck (Figure 45(b)).

A Cycloturbine C2E bearing cartridge and shaft with attached weights were used as the test weight (Figure 45(c)). The combined weight was about 480 pounds. A tie-line was attached to the hoist weight in order to prevent the weight from striking the tower. Another line was strung from the weight in order to apply a downward force on the load. Two men were on the tie-line and one man operated the winch.

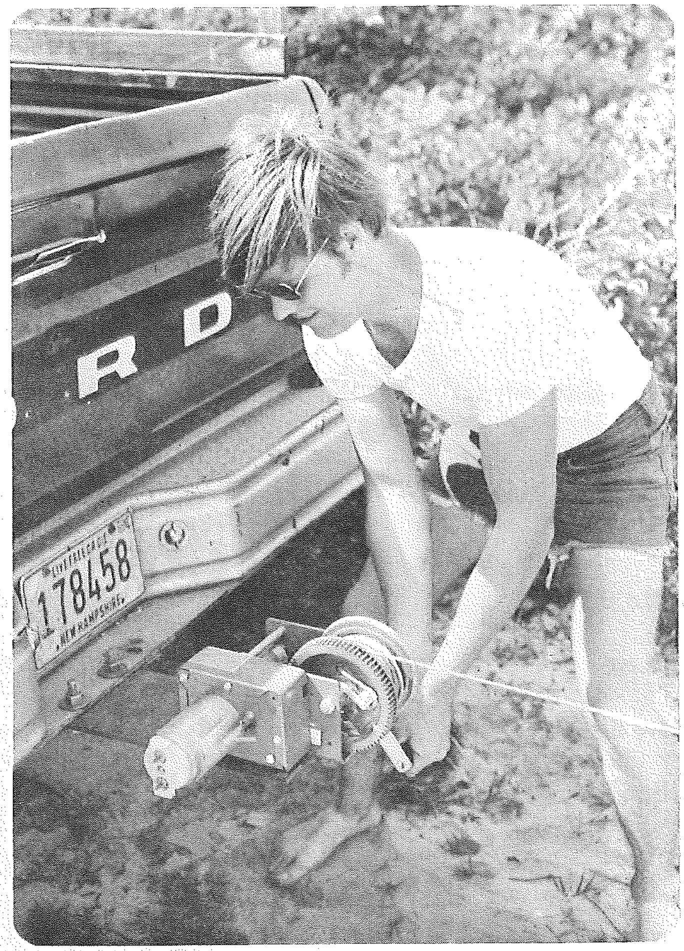
The davit was installed in less than one hour, which was faster than the previous version. The davit hoisted the test weight with no apparent difficulty and easily absorbed the dynamic load. The stays and guy wires on the davit seemed effective in preventing bending in the tubes.

The prototype aluminum davit, which incorporated changes tested on a steel version, was fabricated and tested. A weight of over 500 pounds was lifted and hoisted using the electric winch almost to the top of the tower. A steel support cable which provided tension support to the davit boom was overstressed and parted. An oscillation



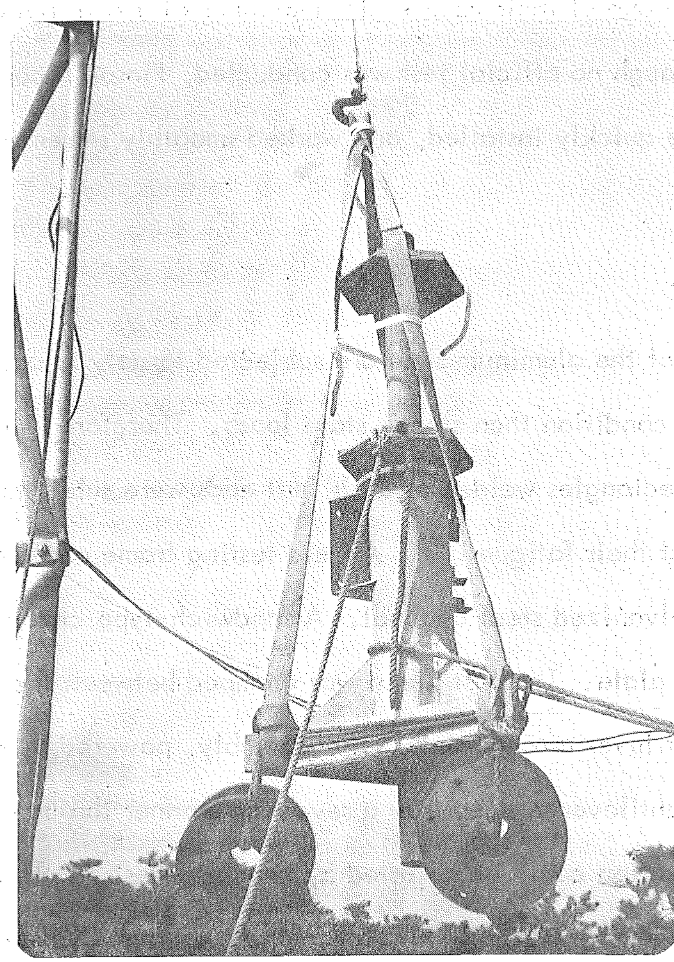

a) Davit Attachment to Tower

Figure 45. Test of Steel Davit.




b) Winch Attached to Truck.

Figure 45. Test of Steel Davit (Continued).



c) Test Weight

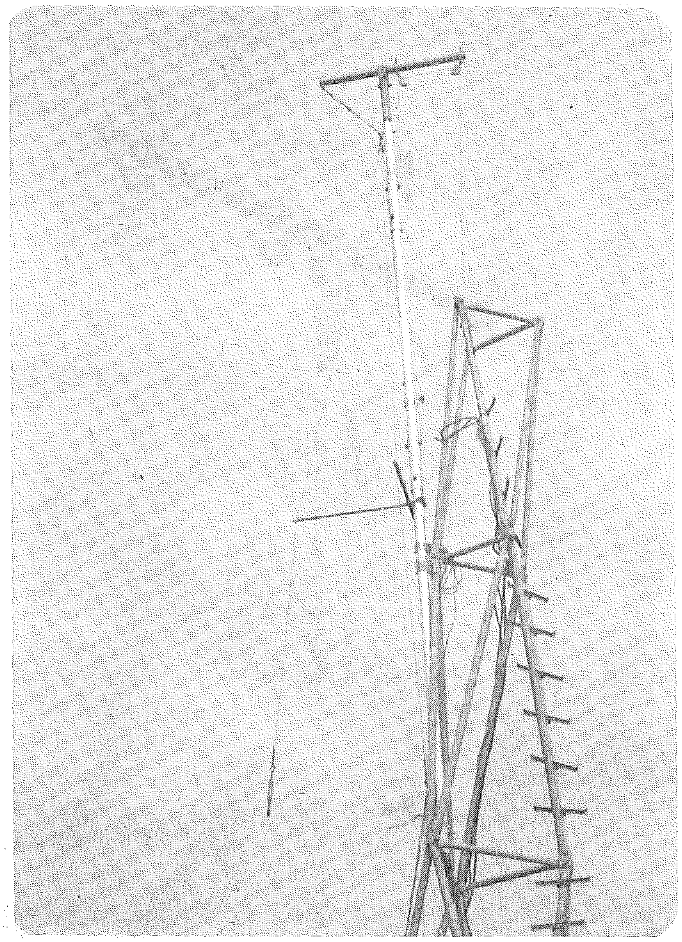
Figure 45. Test of Steel Davit (Concluded).

of the davit occurred and the load bounced up and down. However, the davit withstood the load and the hoist weight was lowered to the ground. Photographs of the prototype davit are included in Figure 46.

Subsequent to this test, Pinson used the prototype davit and the work platform to take down one of their commercial machines at a site inaccessible to crane equipment. Although no official test was conducted, Pinson reported that the davit and platform were quickly installed, and worked smoothly in removing the C2E Cycloturbine.

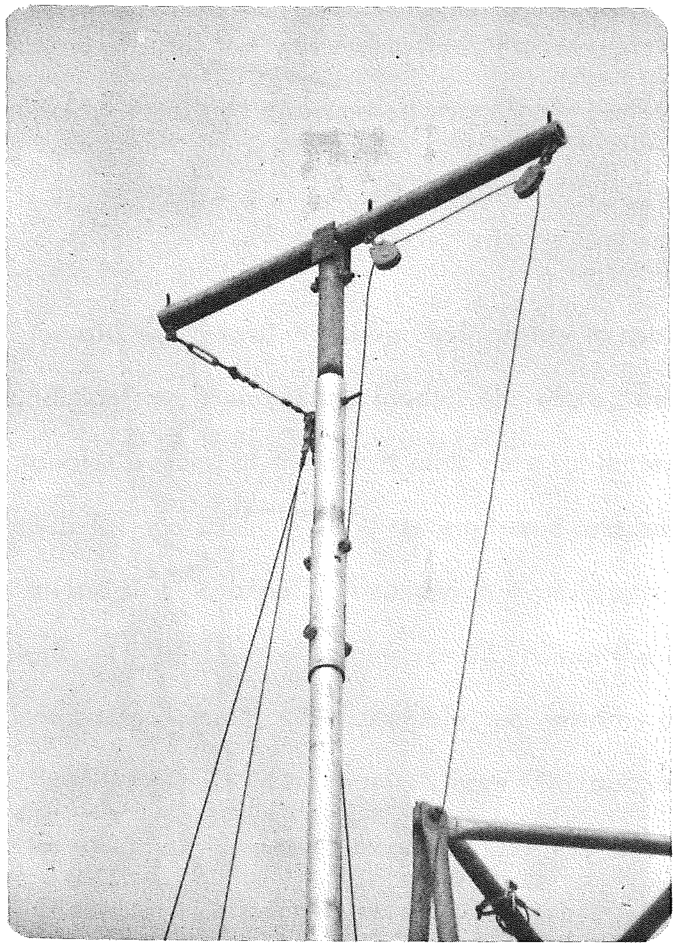
## 5.5 WELDS

Welds of the aluminum strut are subjected largely to oscillatory loads which is a more critical condition than steady state loads. Therefore, weld specimens consisting of aluminum rectangles welded at their butt ends were subjected to cantilever oscillatory loads to test their fatigue life. A weld testing frame and assembly was constructed with 6" x 1/4" galvanized steel channel. A sandwich-type clamp was built of steel channel and steel plate. The test piece was clamped between the channel and the plate, resulting in a cantilever arrangement. The assembly, powered by an electric motor, bent a clamped cantilevered sample in a reversing manner through a system of linkages and levers. Deflection could be adjusted by choosing desired attachment-to-fulcrum-point distances on the levers. The electric motor, equipped with a Gilmer-type toothed belt and pulleys, cycled the specimens approximately 4.1 times per second. An electric clock, hour meter, and microswitch comprised the rest of the electrical equipment. The microswitch was mounted in such a way so that when the test piece failed, the microswitch "opened" and shut down the electric motor, hour meter, and clock.



a) Installed Davit; (Note Parted Cable)

Figure 46. Prototype Aluminum Davit Installation.

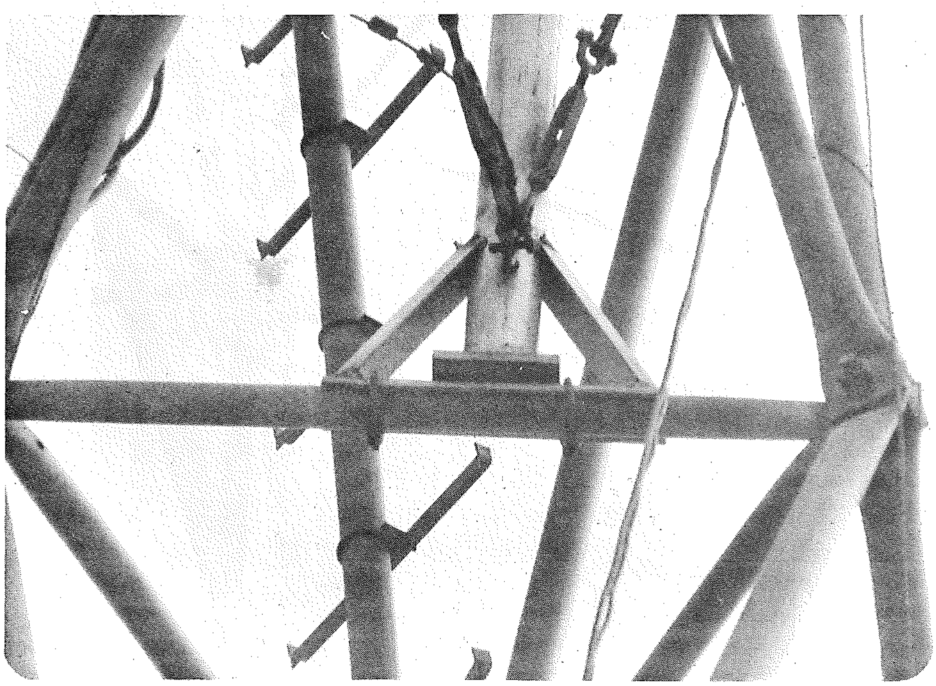


b) Crane

Figure 46. Prototype Aluminum Davit Installation (Continued).

c) Tower Attach Point; Bracing
Stays and Cables

Figure 46. Prototype Aluminum Davit Installation (Continued).



d) Davit Foot Clamped to Tower

Figure 46. Prototype Aluminum Davit Installation (Concluded).

Specimens were subjected to a constant load until failure occurred. A range of loads was applied in order to determine the S-N diagram for the specimen. The S-N curve was compiled for the weld samples based on the elapsed time, oscillation rate (motor RPM) and stress levels (through deflection and moment arm distance). Sample results are shown in Figure 47. In addition, transmission of the oscillatory load was through rod ends selected for the 1-kW high-reliability turbine. Thus, the wearability of these parts was demonstrated by the weld tests. Testing was discontinued when the reliability assessment task was deleted by Rockwell.

SAMPLE 1:

Test Duration = ~120 Hours - 1.77 Million Cycles

Applied Force

Total Testing (Double) Amplitude = x = 0.335

Then

$$0.1675'' = \frac{P(13.25 \text{ in.})^3}{3(10 - 10^6 \text{ psi})(0.013 \text{ in.}^4)}$$

$$P = 28.1 \text{ lbs Force}$$

Bending Stress

$$\delta = \frac{(28.1 \text{ lb})\ 13.25 \text{ in.})\ (0.25 \text{ in.})}{0.013 \text{ in.}^4}$$

$$= 7{,}155 \text{ psi (completely reversing stress)}$$

Weld Stress

$$M_{MAX} = 28.1 \text{ lb } (6 \text{ in.}) = 168.5 \text{ in. lb}$$

$$\delta_{\omega} = \frac{(168.5 \text{ in.-lb})\ (0.25 \text{ in.})}{0.013 \text{ in.}^4} = 3{,}240 \text{ psi}$$

SAMPLE 2:

A second specimen was also tested for 240.5 hours, 3.55 million cycles without failure.

Figure 47. Sample Results of Weld Fatigue Test.

# SECTION 6

# CONCLUSIONS

The ASI/Pinson/NPI 1-kW high-reliability SWECS fabricated during Phase II was basically the same as approved at the Phase I Final Design Review. Testing of the first prototype resulted in a number of design improvements which were incorporated. The most noticeable change was the replacement of the approved tail-vane/wing system with the V-vane configuration. Other changes included redesign of the blade/strut connection and replacement of the 15:1 gearbox with a 25:1 gearbox.

Fabrication was accomplished using standard manufacturing processes. Capabilities to perform all of the required processes were not available in-house, particularly for the turbine. As such, outside contractors had to be used which introduced delays into the fabrication of the prototypes, and, in some cases, introduced quality control problems which had to be resolved.

Testing of components and subassemblies provided design information and verification data required to continue and complete fabrication. Testing of the complete prototype system provided overall confidence in system performance. Initial performance results indicated that the system had an output of 940 watts at 20 MPH, slightly below the design requirement. The peak system power coefficient was determined to be 0.25. Subsequent to obtaining these initial results, the turbine was modified to finalize and improve the design of the automatic control system. Unfortunately, the remainder of the test program, provided little additional insight or data due to unseasonably low winds.

During this extended test period, basic operation of the turbine including automatic shutdown and restart was observed; however, final tuning of the turbine to a prescribed wind speed range was not completed because of inadequate wind conditions. In addition, insufficient electrical data were recorded, again, due to the poor wind conditions.

As a result of the very low winds, the following areas were inadequately explored at the time of delivery of the first prototype:

Electrical

- Complete system never exercised under field conditions.
- Field characteristics had been modified with the possibility that a turbine/electrical system mismatch could result in insufficient power output.
- Voltage regulation was never exercised. Operation at high power levels and in fluctuating power levels with changing battery loads was required to preclude resonant conditions.
- Operation of the dump load circuit was never observed. The dump load should be exercised under varying conditions to preclude limit cycles.

Turbine

- Testing of the turbine following modification of the blades indicated that the machine was now sluggish in startup requiring a wind in excess of 10 MPH. It was suspected that the source of the problem was in the control system.
- Operation of the automatic shutdown/restart system, although demonstrated in moderate winds, was never tested in high winds. Tests in high winds were necessary to ensure proper operation and to establish the proper shutdown/restart wind speed range.
- A Dutch-roll type oscillation was observed on the V-vane. Attachment of the vane was modified but the modification was not tested.

As a result of the above uncertainties, Rockwell decided to conduct controlled velocity tests (CVT) prior to field tests (see Reference 5). Since modification of the turbine relative to the automatic control system, the SWECS has been sluggish in startup. This was observed in the Rockwell CVT. Resolution of this difficulty is of prime importance during the field tests at Rocky Flats.

One of the objectives of the high-reliability program was to develop a technology base for design, fabrication, and production of a high-reliability wind machine in the

1-2 kW size range for use in rural and remote applications. The design proposed and subsequently developed by ASI/Pinson/NPI was based on the technology of the wind industry in 1978. As observed in Reference 2, many trade-offs were made in order to satisfy the high-reliability requirement. One of the design decisions, based on these trade-offs, was to build a 1-kW machine. It is obvious that this would make it very difficult to meet the cost/kW goal. Not fully appreciated at that time, however, was the fact that the cost of a high-reliability electrical system would be approximately 50 percent of the cost of the basic SWECS.

These cost factors, plus the trend of the wind industry to favor utility tie-in, made the commercial production of the newly developed SWECS unattractive. More important factors, however, were present during the development of the ASI/Pinson/NPI SWECS. The high-reliability SWECS was an extrapolation of commercial turbines produced by Pinson. In 1978, relatively few Pinson machines were installed in the field, but those that were provided valuable data such as its ability to withstand hurricane force winds and problems with bearing quality which Pinson brought to bear on the development of the 1-kW turbine.

The interchange was mutual for as the 1-kW high-reliability design progressed, many of the design features and fabrication techniques were immediately added to the Pinson commercial machines. For example, the Cycloturbine C3E3 marketed by Pinson is 16 feet in diameter with 10-foot blades. The blades, while of different planform than the 1-kW SWECS, are constructed in the same manner using a leading-edge extrusion. The struts are also similarly constructed using the Alcoa extrusion and castings at the strut root. Bearings and rod ends are now of the same quality. The main shaft now has the same hubs. The weldment is galvanized. The same trip mechanism is used; in fact, its design was prompted by the need for automatic control of the high-reliability SWECS.

Thus, while the ASI/Pinson/NPI 1-kW high-reliability SWECS is not commercially available at present, the machines commercially marketed by Pinson at this time are a blend of their original design and the high-reliability design.

Field tests of the 1-kW SWECS by Rockwell at Rocky Flats should provide valuable data and insight into the operation of this machine. Of particular interest will be those features introduced to enhance reliability and which should be made available in the marketplace.

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# APPENDIX A

# LIST OF DRAWINGS

# LIST OF DRAWINGS

## TURBINE:

| Drawing No. | Title |
|---|---|
| HRC | General Layout |
| BC-1 | Bearing Cartridge Weldment |
| SH-1 | Shaft Assembly |
| DTM1 | Drive Train Mounting |
| DTM2 | Generator Mount Frame Parts |
| DTM3 | Generator Mount Frame Parts |
| DTM4 | Generator Mount Bar |
| 0400 | Cowl Assembly |
| 0401 | Cowl Mount Strap |
| BA-1 | Blade Assembly |
| | Details (Blade Cross-Section) |
| AF1 | NACA 0015, 6-in. Airfoil Extrusion |
| AF2 | Extruded Leading Edge w/Ballast NACA 0015 |
| ST1 | Upper and Lower Strut Components |
| SRC | Strut Root Casting |
| 1HP1 | Upper Strut Root Gusset #1 |
| 1HP2 | Upper Strut Root Gusset #2 |
| 1HP3 | Lower Strut Root Gusset #1 |
| 1HP4 | Lower Strut Root Gusset #2 |
| 0104 | Connector Plate, Welded |
| 0201 | Lever, Strut |
| 0600 | Tilt Cam Assembly |
| 0601 | Cam Bearing Assembly 1-kW |
| 0602 | Cam Bearing Block |
| 0603 | Cam Lever |
| 0604 | Cam Link |
| 0605 | Cam Tilt Block |
| 0606 | Cam Stem |

| Drawing No. | Title |
|---|---|
| TC2 | Cam Bearing Housing Tilting Spinner Assembly |
| TC3 | Tilting Spinner |
| TC8 | Vane Pedestal |
| 0608 | Tilt Vane Assembly |
| 0607 | Tail Vane |
| VW2 | Vane and Wing Boom Parts |
| 2901 | Swivel |
| 2902 | Lever Support |
| 2903 | Stop Bracket |
| INS 1000 | Instrumentation |
| 1001 | Torque Load Cell 1-kW |
| 1002 | Strain Gage Template |
| 3002 | Instrumentation Bracket, Trump Ross |
| 3003 | Azimuth Indicator Bracket |
| 3004 | Instrumentation Wiring 1-kW |

ELECTRICAL SYSTEM:

| Drawing No. | Title |
|---|---|
| NPI 870105-1 | Schematic - 1-kW Small Wind Energy Conversion System |
| NPI 870105-2 | Block Diagram - 1-kW System |
| A1A1-D1 | Disc for Mounting Terminals of Alternator |
| A1A1-D2 | Cable Attachment at Alternator |
| A1A2 | Alternator Lightning Protection Network |
| A1A2-L1-3 | Detail of Choke Assembly; L1, L2 and L3 of Alternator Lightning Protection Network |
| A1A2-HL | Alternator Lightning Protection Network Box - Hole Location |
| A1A2-PHL | Alternator Lightning Protection Network Back Panel - Hole Location |
| A2A1 | Main Control Lightning Protection Network |
| A2A1-HL | Main Control Lightning Protection Network Box - Hole Location |
| A2A1-PHL | Main Control Lightning Protection Panel - Hole Location |

| Drawing No. | Title |
|---|---|
| A2 | Main Control Panel - Hole Location |
| A2HL | Main Control Box Hole Location |
| A2A2/A2A4 | Main Control Back Plane Layout |
| A2A2/A2A4-CL | Component Layout - A2A2 and A2A4 Circuit Boards |
| A2A2/A2A4-VLL | Main Control Box - Ventilating Louver Location |
| A2SA | Assembly Detail of Drawing A2A2/A2A4 |
| A2A3 | Side View - 1/2 Main Rectifier |
| A2SB | Assembly Detail, Main Rectifier |
| A2-D | F-3 Bracket and Heat Sink Detail |